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EVALUATION OF CHEMICAL EXPLOSIONS AND METHODS OF DISCRIMINATION FOR PRACTICAL SEISMIC MONITORING OF A CTBT

Vitaly I. Khalturin
Tatyana G. Rautian
Paul G. Richards
Won-Young Kim

Lamont-Doherty Earth Observatory
of Columbia University
Palisades, NY 10964

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29 Randolph Road
AIR FORCE MATERIEL COMMAND
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Katharine Kadinsky-Cade
KATHARINE KADINSKY-CADE
Contract Manager

Charles P. Pike
CHARLES P. PIKE, Deputy Director
Integration and Operations Division

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Vitaly I. Khalturin, Paul G. Richards
Tatyana G. Rautian, Won-Young Kim

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13. ABSTRACT *(Maximum 200 words)*

Our Final Report is in three parts. Part one is a stand-alone paper, submitted for publication, entitled "The Seismic Signal Strength of Chemical Explosions." In this paper, we have compared the seismic magnitude of a wide variety of chemical explosions to the magnitude expected for explosions set off in hard rock under conditions most favorable for generating strong seismic signals. We define the *deficit* of an explosion, as this largest magnitude, minus the actual magnitude. In practice, the deficit is found to be around 1.5 to 2 magnitude units, for the great majority of explosions. Part two is a stand-alone paper, entitled "Magnitude Distribution of Mine Blasting Activity In Different Regions." In this paper we survey more than 30 regions of the world and conclude that not more than a few hundred mine blasts per year occur with magnitude ≥ 3.5. Part three is a brief report on work we have published concerning discrimination of explosions, using three-component seismic data.

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Part 1 of this Final Report consists of the following paper, submitted for publication in the Bulletin of the Seismological Society of America:

THE SEISMIC SIGNAL STRENGTH OF CHEMICAL EXPLOSIONS

Vitaly I. Khalturin, Tatyana G. Rautian and Paul G. Richards[1]
Lamont-Doherty Earth Observatory of Columbia University
Palisades, NY 10964
([1]also, Department of Earth and Environmental Sciences, Columbia University)

ABSTRACT

We have compared the seismic magnitude of a wide variety of chemical explosions of known yield, to the magnitude expected for explosions set off in hard rock under conditions most favorable for generating strong seismic signals. Our results are based on numerous chemical explosions that include several different broad groups, mostly taken from practical experience with explosions carried out on territory of the former Soviet Union. To quantify these observations, we define the *deficit* of an explosion as the expected signal strength if that charge size, or yield, were fired under the most favorable conditions in hard rock, minus the actual strength. We document the size of the deficit using two different measures of signal strength: the energy class, K; and the seismic magnitude (which may be the teleseismic m_b or a regional magnitude).

In general, for ripple-fired chemical explosions carried out in the mining and construction industries, the magnitude deficit is around 1.5 to 2. The type of blasting that comes close to the maximum coupling efficiency (zero deficit) is now rare except for small yield single-fired explosions that are specially designed to maximize signal strength (such as explosions for seismic refraction surveys). There are a small number of locations where the deficit is small (~ 0.5 magnitude units), for quite large chemical yields (several hundred tons). Such explosions, which appear to be uncommon and declining as blasting practices are modernized, may require special attention in the context of verification of the Comprehensive Test Ban Treaty.

INTRODUCTION

For more than 15 years following negotiation of the Threshold Test Ban Treaty in 1974, intensive study was made of the relationship between the seismic magnitude and the yield of underground nuclear explosions (UNEs). For conditions typified by the Soviet Union's main test site (closed in 1991), near Semipalatinsk, Kazakhstan, much work has been summarized by Ringdal, Marshall and Alewine (1992) as the relationship

$$m_b = 4.45 + 0.75 * \log Y \qquad \text{for yield } Y \text{ in kilotons.} \tag{1}$$

Their result is thought to apply to shield regions that include much of North America and Eurasia, but can be different in tectonically active regions. For example, for well-tamped contained explosions below the water table at the Nevada Test Site in the western U.S., the corresponding relation is given by Murphy (1981) as

$$m_b = 3.92 + 0.81 * \log Y. \tag{2}$$

These two equations indicate that a UNE at Semipalatinsk has seismic magnitude about 0.5 units larger than a UNE of the same yield at the Nevada Test Site (if both explosions are in hard rock, below the water table).

When estimates began to be made, in the early 1990's, of the numbers of chemical explosions set off routinely in industrialized countries, there was concern that the seismic signals from such explosions would be so numerous, and would appear so similar to the signals expected from a small UNE, that they would swamp efforts at CTBT monitoring based on seismological methods. The reasoning behind such pessimism was that the United States, Russia, China, and numerous non-nuclear-weapon states such as Australia, Canada, Kazakhstan, and countries of South America use a total of about five megatons of chemical explosive per year. This overall total is distributed across numerous blasts of total charge size ranging above one kiloton (on the order of a few hundred per year); between 100 and 1000 tons (thousands per year); and between 10 and 100 tons (many thousands per year). These estimates are based upon Richards et al. (1992) for the U.S, Khalturin et al. (1996) for territory of the former USSR, communications to the Conference on Disarmament by Australia and Canada, and personal communication by W. Leith for South America. If these charge sizes were interpreted via (1), then one would expect chemical explosions to generate hundreds of events each year with magnitude greater than 4.5; thousands of events per year in the magnitude range 3.5 – 4.5; and several events *per hour* in the range 3 – 3.5 (a magnitude range that includes the source strength predicted for a fully-decoupled UNE of around 5 kilotons).

This expectation, however, turns out to be far from the facts, because it is clear from seismicity bulletins (global and regional), published by numerous organizations, that the actual numbers of seismically detectable chemical explosions are on the order of a hundred times smaller

than the above predictions (Rivière-Barbier, 1993; Richards, 1995; USGS mining seismicity bulletin for the U.S. for the period May-October 1997).

A natural way to try to improve estimates of the numbers of chemical explosions observed at given magnitude levels would to be find the coefficients a and b in magnitude–yield relationships of the form $m_b = a + b * \log Y$ derived for chemical explosions in different regions, and then to predict the number of events at different magnitudes from knowledge of the distribution of explosive between blasts of different size. But such an approach fails because chemical explosions do not exhibit a good fit to a linear relationship between magnitude and log yield, even when restricted to a particular mining region.

Instead, we have approached the issue quantitatively, but at a less detailed level. Our approach has been to determine the upper limit $M(Y)_{max}$ for the magnitude of an explosion (chemical or nuclear) at given yield Y for numerous different explosions carried out under different conditions in hard rock and in different tectonic provinces; and then to compare the magnitude of an explosion of interest (of known charge size or yield) with the upper magnitude limit for that yield. We find that typical chemical explosions carried out by the mining and construction industries are highly inefficient at generating seismic signals—as compared to this upper limit. For quantitative purposes, we propose that the observed inefficiency of seismic signal generation can usefully be described by the *deficit*, defined as the difference in source strength for a given explosion with a particular charge size, between that *predicted* for a well-coupled explosion at that charge size (yield) and under conditions of efficient signal propagation, and the *actual* source strength. (Signal strengths here are based on logarithmic scales, so the deficit implies not a difference, but an extra factor, if a linear strength scale were used.) We find that this deficit, which is subject to considerable scatter, can nevertheless be roughly estimated for different broad groups of chemical explosions. The deficit is commonly around 1.5 to 2 magnitude units for chemical explosions carried out in the mining and construction industries—which is why the great majority of blasts that would be counted as large in terms of charge size, are not detected seismically. In some cases for very large commercial blasts the deficit can be larger—around 3 magnitude units. Below, we comment on an apparent lack of any systematic difference in maximum coupling efficiency, between chemical and nuclear explosions.

Given the number of factors that contribute to the deficit, we were gratified to find that it was indeed possible to obtain useful summary information. The three principal factors contributing to the deficit are: details of blasting practice, such as shot depth, how many individual charges were fired, and the pattern of delays; the local geological conditions; and the efficiency of propagation of seismic signals, once they have been excited at the source.

The following sections report our available data, and methods of analysis. We present evidence that the upper limit in magnitude for explosions of known yield in hard rock, under favorable propagation conditions, is given by the relation

$$M(Y)_{max} = 2.45 + 0.73 * \log Y \text{ (tons)} = 4.64 + 0.73 \log Y \text{ (kt)}$$

and the upper limit in energy class, again for hard rock, is

$$K(Y)_{\max} = 7.0 + 1.55 \log Y \quad (Y \text{ in tons}).$$

To obtain the coefficients in these equations with acceptable confidence, the observational data must be studied over as wide a range of yields as possible, including well-coupled explosions at both high and low yields. Once the upper limits have been obtained we are able to comment upon the magnitude deficit for explosions that are not well-coupled into seismic energy propagating with maximal efficiency. We briefly discuss the properties of explosions underwater or in soft saturated rock such as clay—which couple into seismic energy even more efficiently than the upper limit for hard rock. For such super-efficiently coupled events it is natural to speak of their magnitude *excess*. Finally, we comment on possible implications for the verification regime of the Comprehensive Test Ban Treaty opened for signature in 1996.

AVAILABLE DATA

We have acquired data on charge size, or yield, of a wide variety of chemical and nuclear explosions, together with data on seismic source strength. Our emphasis has been on the former Soviet Union, for which we have data on chemical explosions from about thirty regions (Khalturin et al, 1996). We also report data from Israel, Germany, China, and North America. Our data on source strength in some cases come from measurements of the energy class, K; and in other cases come from a seismic magnitude—teleseismic m_b for large events, otherwise a regional magnitude based upon P_n or L_g waves or upon a coda measurement.

It was important to include the use of energy class K in our study, as the only measurement of seismic source strength reported for many explosions (and earthquakes) on territory of the former Soviet Union (FSU). The K scale (Rautian, 1960) has been in use since the late 1950's up to the present time to characterize the size of locally- and regionally-recorded events at distances from a few km up to 2000 km. It is based upon the sum of amplitudes A_p and A_s of both P and S (or Lg) waves on short-period instruments. K is called a measure of the energy class because it is equal to the value of log E, where E is an estimate in joules of the radiated seismic energy. K is still the standard measure of source strength as reported in regional catalogs of the FSU. An increment of K by one unit corresponds to an increment of $\log(A_p + A_s)$ by 0.56 units.

We obtained the relationship between magnitude and K for several sets of earthquakes and explosions, using magnitudes reported by the International Seismological Centre (ISC), the British Atomic Weapons Establishment (AWE), and by NORSAR. In Figure 1 are shown examples of m_b vs. K for underground nuclear explosions in the Degelen subarea of the Semipalatinsk Test Site, and for chemical explosions at the same test site. Both cases are well fit by the relation

$$m_b = 0.46\,K - 0.64 \qquad (\text{or } K = 1.39 + 2.17\,m_b). \tag{3}$$

Note that m_b 3.0 corresponds to a K value close to 8, and m_b 3.5 to a K value close to 9.

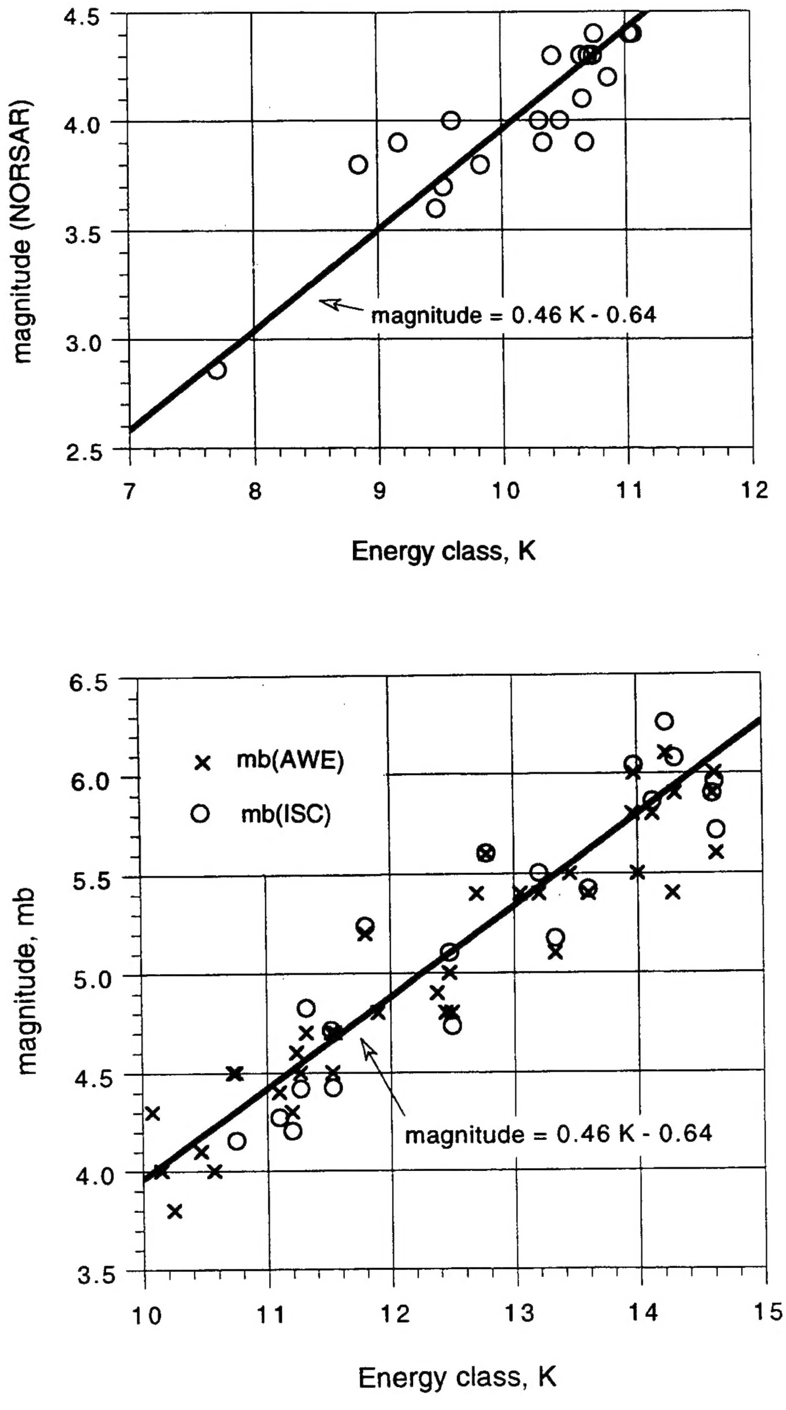


Figure 1. Relation between m_b and K for chemical (top) and underground nuclear (bottom) explosions at the Semipalatinsk Test Site. The solid line in both cases corresponds to the relationship: $m_b = 0.46\,K - 0.64$. Consequently, $\Delta m = 0.46\Delta K$.

Table 1. Region, type and number of explosions with known yield Y and energy class K and/or magnitude M, which we use for estimation of seismic efficiency

Region	Type of chem. explosion	Number of events with known K	M
Central Asia	Experimental:		
	underground	5	5
	surface	5	-
Central Asia, Caucasus	Canal or dam construction	20	13
Apatity, Kola Peninsula	Mining	188	117
Medeo, North Tien Shan	Quarry	61	-
Tekeli, North Tien Shan	Quarry	20	-
Kotur-Bulak, North Tien Shan	Quarry	19	-
Tyrnauz, Caucasus	Mining	39	-
Krivoy Rog, Ukraine	Mining	5	4
Kuzbass, W. Siberia	Coal mine	3	-
Semipalatinsk Test Site, East Kazakhstan	UNEs	24	26
Tadjikistan	Underwater	87	-
Gold Mine, Nevada	Mining	-	61
Israel	Quarry blasts	-	50
	Road construction	-	19
	Underwater	-	3
Kursk Magnetic Anomaly, Russia	Mining	-	9
New Mexico	Experimental, on the surface	-	2
Nevada Test Site	Experimental, NPE	-	1
Zhuhai, China	On the surface	-	1
Vogtland, Germany	Mining	-	12
WW2 mine detonation, England	Disposal		1
Offshore, United Kingdom	Underwater		1
Total		476	325

Table 1 names the regions, types, and numbers of explosions on which we report here. These sets of explosions were taken to cover as wide a range of yield and magnitude as possible, paying special attention to explosions for which the chemical energy was well-coupled into energy of seismic waves. We have used chemical explosions with charge size ranging from 0.08 tons up to 11120 tons. Our data come from more than thirty regions of the FSU and elsewhere, and include 476 chemical explosions with known K (5.0 to 15.0) and known Y; and 311 chemical explosions with known magnitude (0.3 to 6.25) and known Y. We also used magnitude data for 26 nuclear explosions at the Semipalatinsk Test Site with yield from 230 tons up to 165000 tons. Note that there is considerable overlap, in yield, between the sets of chemical and nuclear explosions. Besides K values and m_b for explosions with known Y, we collected local magnitudes (*ML*) and coda magnitudes (*MC*). We appreciate that work is needed to reconcile various regional magnitudes scales with the standard teleseismic scale, m_b, but available scales are still useful for preliminary estimates of the magnitude deficit of different explosions.

The theory and practical methods of employment of large chemical explosions was a well advanced subject in the former Soviet Union, for example in the construction of dams and canals. Many of these explosions were in the kiloton range and were detected teleseismically, as well as by special monitoring systems deployed from very close to the shot point, out to local and regional distances of several hundred km. Most interesting, were a number of experimental well-contained single-fired underground explosions made under experimental conditions most favorable for generating seismic signals (for example, in the Kazakhstan platform). Such explosions, together with special sets of small industrial explosions in hard rock, indicate the upper limit of the magnitude – yield relation at fixed yield.

Table 2 gives basic information on 38 large well-documented chemical explosions whose parameters were used in our study. For some of these explosions we have results of near-field observations, and for most of them we have regional data that were used to assign the K value. Thus the K values are assigned from regional data, and m_b values are taken from the ISC or NEIC (or the average of these if both are available). *MLH* is a Russian scale similar to M_s, that is based on amplitude/period of surface waves; $MLH \sim M_s + 0.15$.

The shots of 1957 (in Uzbekistan), 1959 and 1960 (in Tuya-Muyun, Kyrgyzstan) and 1961 (in the Degelen subarea of the Semipalatinsk Test Site, Kazakhstan) are of interest in the history of nuclear testing and CTBT negotiations. Technical details of the 1000 ton cratering shot Arys, of 1957, were quickly circulated and referred to in Geneva negotiations (see also Pasechnik et al, 1960). The other three (190, 660, and 600 tons respectively) were carried out underground as single-fired shots in order for the Soviet Union to acquire practical experience, for example with containment, prior to carrying out a program of underground nuclear explosions—but few details on these shots emerged until the 1990's. Large well-tamped chemical explosions that are single-fired and at a depth permitting complete containment are very unusual. (In the US the only comparable example would appear to be the "chemical kiloton" Non-Proliferation Experiment of 22 September 1993). The 660 ton shot of 1960 was reported by the Soviet delegation in early

Table 2. Large and/or well documented industrial or experimental chemical explosions on territory of the former Soviet Union

Region	Date	GMT	Yield	K	mb	MLH	Lat. N	Long. E	Purpose
Arys Uzbekistan	19 Dec 57	09:00:00	1000	10.5	-	3.1	42.204	69.000	Science
Pokrovsky Urals (shots fired at shallow depth over a line more than 3 km in length)	25 Mar 59	09:00:00	3100	-	4.8	4.0	60.2	59.9	Canal
Tuya-Muyun Kyrgyzstan	31 Dec 59	09:00:00	190	9.9	-	3.3	40.353	72.588	Science-Military
Tuya-Muyun Kyrgyzstan	03 Mar 60	09:00:00	660	10.6	-	-	40.354	72.588	Science-Military
Degelen Semipalatinsk Test Site	05 Jun 61	03:50:00	600	10.9	4.42	-	49.773	77.983	Military
Dzhezkazgan Kazakhstan, on the surface	20 Nov 65	07:00:00	1152	9.5	-	-	48	67	Military
Medeo Almaty	21 Oct 66	04:59:59	1689	11.4	-	-	43.154	77.061	Dam
Medeo Almaty	21 Oct 66	05:00:03	3604	11.8	-	3.7	43.154	77.061	Dam
Medeo Almaty	14 Apr 67	05:00:09	3940	11.0	-	-	43.154	77.061	Dam
Baypazy Tadjikistan	29 Mar 68	06:48:42	1944	10.4	-	-	38.24	69.15	Dam
Akh-Su Dagestan	26 Dec 72	04-08-57	552	9.4	-	-	43.0	47.1	Dam
Tyrnyauz Caucasus	31 Dec 77	12:00:00	833	9.4	4.0	-	43.36	42.83	Mining
Degelen Semipalatinsk Test Site, on the surface	31 Jul 78	08:00:00	5000	10.2	-	-	50.42	77.87	Military
Kazakhstan Near Almaty, on the surface,	28 Nov 81	02:31:00	251	8.22	-	-	43.8	76.85	Science
Tyrnauz Caucasus	27 Dec 81	07:44:21	1075	10.2	4.0	-	43.36	42.83	Mining
Urgench Turkmenistan	26 Dec 82	05:29:00	2550	12.4	4.8	-	40.98	61.68	Reservoir
Bukhara-1 Uzbekistan	23 Mar 83	11:07:57	1960	11.3	4.6	-	39.24	64.34	Canal
Bukhara-2 Uzbekistan	22 Apr 83	03:56:22	2426	11.37	4.8	3.9	39.34	64.24	Canal

(Table 2, continued)

Bukhara-3	16 May 83	12:07:51	1690	11.3	4.7	-	39.31	64.33	Canal
Uzbekistan									
Bukhara-4	26 May 83	12:46:22	3830	10.65	4.5	3.8	39.23	64.27	Canal
Uzbekistan									
Bukhara-5	15 Jun 83	13:34:03	4140	12.0	4.8	-	39.31	64.36	Canal
Uzbekistan									
Kosh-Bulak	25 Jun 83	20:35:14	2550	11.9	4.5	-	40.860	61.653	Dam
Turkmenistan									
Bukhara-6	02 Jul 83	11:42:21	2560	11.5	4.8	4.2	39.22	64.36	Canal
Uzbekistan									
Bukhara-7	11 Jul 83	14:47:56	3460	11.1	4.6	-	39.23	64.38	Canal
Uzbekistan									
Bukhara-8	27 Aug 83	05:04:42	2280	11.15	4.55	4.1	39.24	64.47	Canal
Uzbekistan									
Alinjachai	04 Sep 84	09:00:00	689	10.4	-	-	39.146	45.427	Dam
Caucasus									
Balapan	15 Sep 84	06:15:09.7	?	10.80	4.7	-	49.992	78.881	Military
Semipalatinsk Test Site									
Quisa	16 Dec 84	11:00:36	437	10.0	-	-	42.312	43.385	Dam
Caucasus									
Degelen	27 Jun 85	12:57:00	500	8.5	-	-	49.73	78.10	Military
Semipalatinsk Test Site, at the surface									
Degelen	29 Jun 87	05:55:00	500	8.5	-	-	49.73	78.10	Military
Semipalatinsk Test Site, in the crater of 27 June 1985									
Novaya Zemlya	25 Aug 87	15:00:00	1000	-	-	-	73.38	54.78	Military
On the surface									
Karaganda	2 Sep 87	07:00:00	9	-	3.05	-	50.28	72.17	Science
Central Kazakhstan, Joint US-USSR Experiment. "Chemex-1"									
Degelen	2 Sep 87	09:27:05	20	-	2.7	-	50.00	70.34	Science
Semipalatinsk Test Site, Joint US-USSR Experiment. "Chemex-2", blowout									
Karaganda	3 Sep 87	07:00:00	9	-	3.1	-	50.28	72.17	Science
Central Kazakhstan, Joint US-USSR Experiment "Chemex-3"									
Uch-Terek	11 Jun 89	06:59:47.5	827	-	-	-	41.644	73.289	Dam
Kyrgyzstan									
Uch-Terek	11 Jun 89	06:59:52	1088	11.1	4.8	4.3	41.644	73.289	Dam
Kyrgyzstan									
Arkhangelsk	27 Feb 91	11:25:18	1000	-	4.5	-	62.95	41.88	Military
North Russia									

negotiations as the seismic equivalent of 5 kt fired "under RAINIER conditions" (referring to the first contained underground nuclear explosion, carried out by the U.S. at the Nevada Test Site in September 1957—the first Soviet underground nuclear explosion was in October 1961, also at Degelen). The early Soviet report is understandable today in the context of what we now know about the magnitude bias between the Nevada and Semipalatinsk Test Sites. But in October 1960 Albert Latter, co-author of the original paper on decoupling, wrote that "I personally do not accept the Russian statement because they have not given any confirmatory details" (Latter, 1960).

METHOD OF ANALYSIS

Essentially, our approach began with plotting values of K, or magnitude, against log Y for numerous chemical and nuclear explosions in hard rock. The next step was to obtain the position of a straight line that could serve as the upper limit on K, or magnitude, at different values of log Y. The position of this line, $K = K(Y)_{\text{max}}$ or $M = M(Y)_{\text{max}}$, was taken to pass through or above almost all the data points, the exceptions being a small number of points whose position above the line could be ascribed to uncertainty in assigning the magnitude value.

After the upper limit lines have been determined, we define the *energy class deficit* ΔK of a given explosion with known charge size or yield, and whose K value has been measured, as

$$\Delta K = K(Y)_{\text{max}} - K_{\text{measured}}. \tag{4}$$

Similarly for the *magnitude deficit* Δm, we have the definition

$$\Delta m = M(Y)_{\text{max}} - m_{\text{measured}}. \tag{5}$$

where the measured magnitude may be m_b or a regional magnitude. In accordance with (3), the relation between Δm and ΔK is

$$\Delta K = 2.17\ \Delta m \qquad \text{or} \qquad \Delta m = 0.46\ \Delta K. \tag{6}$$

The lower the seismic efficiency of the explosion, the greater the magnitude deficit. We shall find that the deficit can range up to about 3 magnitude units, part of which may be due to the magnitude bias associated with an attenuating propagation path. For very efficient seismic coupling in a region with low attenuation paths to the stations reporting magnitude values, the deficit is low, in the range about 0 to 0.3. The deficit can be found for individual explosions, or averaged for a set of explosions from the same region, over a range of yields.

In the case of explosions under water or in water-saturated clay, rather than the hard rock environment for which our upper limit relationships are derived, the ΔK and Δm values defined by (4) and (5) can be negative and it is natural to reverse their sign and to speak of the magnitude *excess* rather than the deficit. We give examples below.

Within the framework of an upper limit on magnitude for an explosion at given yield in hard rock, and a definition of the deficit, we are interested in seeing if chemical and nuclear explosions have the same upper limit, and if the upper limit is valid and useful for sets of data other than those we present in this paper. Below, we argue that all these questions are answered affirmatively.

UPPER LIMIT OF ENERGY CLASS *K* VS. YIELD

To get the relationship between maximum values of K and $\log Y$, we used data as summarized in Figure 2 that span the range from about 80 kilograms to 165 kilotons—more than a factor of a million. The straight line of points is

$$K(Y)_{\max} = 7.0 + 1.55 \log Y \;\; (Y \text{ in tons}) = 11.65 + 1.55 \log Y \;\; (\text{kt}) \tag{7}$$

which divides the region of the graph that is filled with data points, from a region that has almost none. Only three points lie above the line, and they do so by amounts on the order of 0.1 – 0.2 K units—which is about the error of K determination. All nuclear explosions shown in Figure 2 took place at the Semipalatinsk Test Site. They lie in a narrow band about the line, with K deficit typically from 0 to 0.8. The level of the line (7) is controlled at high yield by underground nuclear explosions (UNEs) and some large chemical explosions. At low yields, it is controlled by small chemical explosions from three quarries in North Tien Shan (including the small Medeo explosions).

Table 3 shows the yield range, the energy class, and the K deficit, for each main data set shown in Figure 2. The last two columns indicate average values of the deficit ΔK and of the corresponding Δm, obtained from ΔK via (6).

The range of Y values from 230 tons to 4000 tons is covered in our data by big chemical explosions as well as by small nuclear explosions. For chemical explosions it appears that the K deficit may be a little larger. The chemical explosions used to create dams or canals were not fired as single charges but were distributed in space in order to move large amounts of rock, and such sources are not as compact as UNEs. But typically the total charge of each of these blasts was fired within a very short period of time, like a single-fired explosion. Their energy class deficit is seen to be small, varying between 0 and 1.5 to 2.0, and is about 1.0 on average.

Five events that were single-fired explosions on the surface, without any covering materials, have larger deficit, amounting to about 2 to 3 K units.

There is a "gap" in the values of K, for Y about 100 tons. This is probably due to an important difference in seismic coupling efficiency, between big single-fired and big ripple-fired industrial explosions in quarries. The term "ripple-firing" refers to the practice called "delay firing" by the mining community. This type of explosion occurs in Apatity (Kola Peninsula, Russia); Krivoi Rog (Ukraine); and Tyrnauz, (South Caucasus, Russia). Taking the ripple-fired explosion data together, we get the impression that over a wide range of Y values, from 0.5 to 500 tons, the

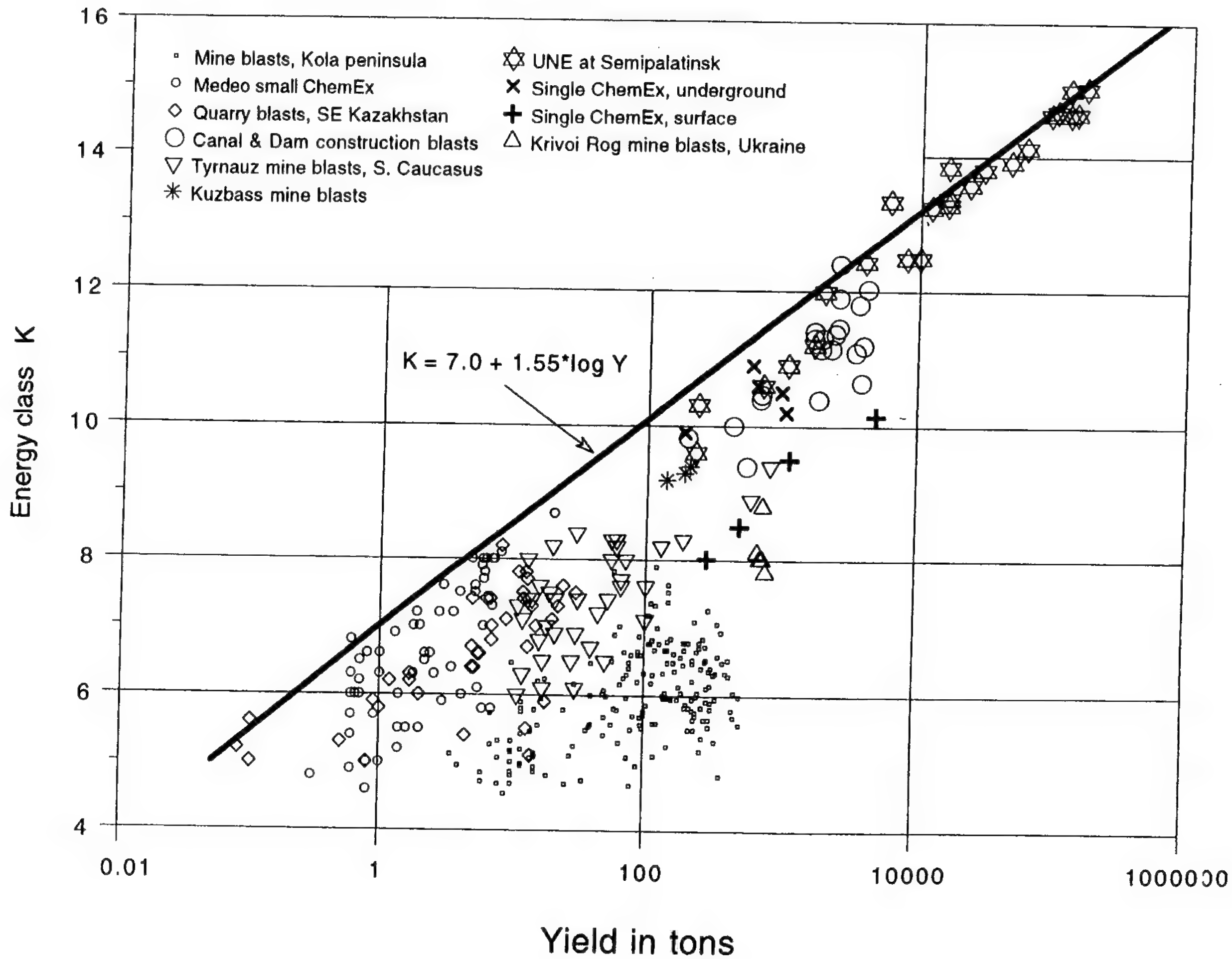


Figure 2. Energy class K versus Y (in tons) for several sets of explosions. The solid line:

$$K(Y)_{max} = 7.0 + 1.55 \log Y \text{ (tons)},$$

is the upper limit for all observed K vs Y data. In the kiloton range this line is controlled by underground nuclear explosions at the Semipalatinsk Test Site and in the low-energy range by chemical explosions from the North Tien Shan. Further details in Figure 3.

energy class K has only a weak dependence on Y. For all these events K is about the same: about 6.5 on average, and is scattered between 5 and 8, with deficit reaching 4 to 6 units.

Five explosions were available from Krivoi Rog, Ukraine, with both yield and K information. They are of nearly the same Y value, about 600 to 800 tons. Their K value is as small as 6.5 to 8, with deficit 2.5 to 3.5.

The left side of Figure 2 is dominated by data from small industrial explosions, many with small deficit, that took place at Almaty and Kotur-Bulak (Kazakhstan) and Medeo (North Tien Shan). These explosions strongly limit the position of the upper limit line in the low yield range.

The Medeo explosions, to the south of Almaty, provided rock used to increase the elevation of a dam.. The Medeo region is composed of hard granitic rocks. The K deficit for these Medeo explosions, with yield from a few tenths of a ton up to a few tens of tons, is never more than 2, and some of them have deficit close to 0. These explosions were single-fired.

Table 3. The energy class deficit ΔK for different sets of explosions

Explosions	Figure #	Y, tons min - max	Class K min - max	Deficit min - max	ΔK aver.	Δm *
Experimental	3e	190 - 1000	9.9 - 10.9	0.6 - 1.4	1.0	0.45
Canal	3e	1700 - 5400	10.7 - 12.1	0.6 - 1.9	1.25	0.55
Dam	3e	200 - 4000	9.4 - 11.9	0.4 - 2.0	1.1	0.50
Surface	3e	290 - 5000	8.2 - 10.2	2.4 - 2.9	2.7	1.25
Apatity	3a	4 - 500	4.6 - 7.9	2.2 - 6.0	4.0	1.85
Medeo	3d	0.3 - 20	4.8 - 8.6	-0.08- 2.2	0.8	0.35
Tekeli	3c	0.1 - 14	5.0 - 8.2	-0.2 - 1.8	0.9	0.40
Kotur-Bulak	3c	0.5 - 30	5.0 - 7.6	1.0 - 3.5	1.5	0.70
Tyrnauz	3b	10 - 1100	6.0 - 10.2	0.7 - 3.2	2.0	0.90
Krivoy Rog	2	680 - 820	7.8 - 8.8	2.8 - 3.8	3.3	1.50
Kuzbass	2	150 - 290	9.1 - 9.4	1.2 - 1.6	1.4	0.65
Underwater (Tajikistan)	2	1.28	7.1 - 8.1	-1.0 - 0	-0.75	-0.35
Underground (nuclear explosions, Semipalatinsk)	2	0.23K - 165K	9.8 - 15.0	-0.3 - 1.0	0.45	0.20

* Δm calculated from ΔK using the relationship $\Delta m = 0.46\ \Delta K$ and rounding to nearest 0.05.

Further detail on the relationship between K and yield is given in Figure 3, showing four sets of data from separate regions. These are arranged in order of decreasing deficit, from the lowest seismic efficiency (Apatity) to the highest (Medeo). Looking at Figures 3a–3d, the difficulty of estimating the upper limit (7) from any single data set is apparent. Only for the Medeo region, where yield changes over a large range (more than a factor of 100000) and the explosions were very well-coupled, is the upper limit well indicated. In Figure 3e, the large industrial explosions to build dams and canals were remarkable efficient generators of seismic waves.

In Table 3, the K deficits (min, max and average) are pointed out for various different groups of chemical explosions, and for UNEs. Besides the question of how the shot was emplaced and whether it was ripple-fired or single-fired, there is also an effect from the geophysical nature of the region in which the explosion was carried out. The most efficient shots (lowest deficit) were chemical and nuclear explosions conducted in the Kazakhstan platform, namely, the UNEs and chemical explosions at the Semipalatinsk Test Site, and chemical explosions in North Tien Shan. The well-tamped Tuya Muyun experimental explosions in Kyrgyzstan were less effective in generating seismic signals than northern Kazakhstan explosions. Dam explosions in the Caucasus region were less effective than similar explosions in Central Asia. Effects of regional variation, presumably due to regional wave propagation variability, are even more apparent in our magnitude – yield data than for energy class – yield, because of the wider range of geophysical regions for which magnitude data are available. This result is demonstrated in the following section.

UPPER LIMIT OF MAGNITUDE VS. YIELD

Figure 4 shows our summary data on magnitude and log Y for numerous chemical and nuclear explosions. We found

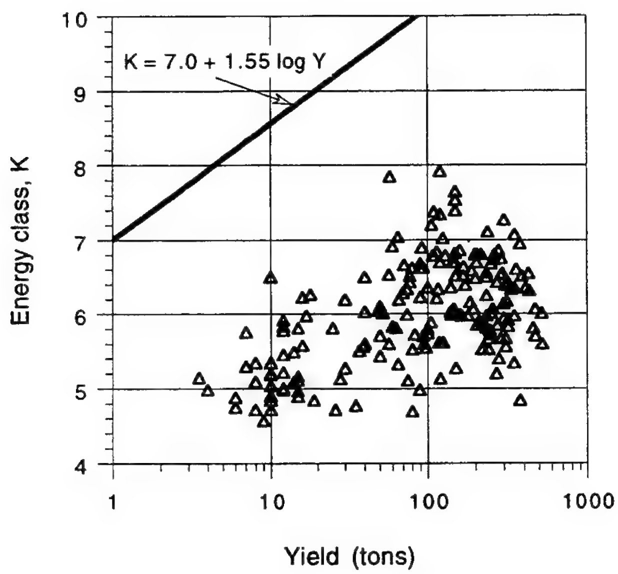
$$M(Y)_{\max} = 2.45 + 0.73 * \log Y\,(\text{tons}) = 4.64 + 0.73 \log Y\,(\text{kt}) \tag{8}$$

for the straight line representing the upper level of magnitude at given Y.

Equation (8) runs quite closely through two small single-fired chemical explosions in Kazakhstan (these were calibration shots a few hundred km from the Semipalatinsk Test Site, arranged in 1987 by the Natural Resources Defense Council and the USSR Academy of Sciences, executed in a way that maximized the seismic coupling—see Given et al, 1990). The line is also close to the controlled detonation of a World War 2 mine (in England on 1994 May 25: ISC data). Unfortunately, at low yield these were the only three well-tamped chemical explosions with known magnitude in high-Q regions. Other explosions such as the Apatiti and Israeli sets were ripple-fired with low efficiency. The line runs just above most of the UNE data and close to most of the large single-fired chemical explosions. In choosing the line (8), we had in mind, in addition to the values shown in Figure 4, the magnitude values that would be obtained via (3) from the K values shown in Figures 2 and 3d for the North Tien Shan quarries in south-east Kazakhstan and the

small Medeo explosions. Such a conversion from K to m_b would give a magnitude around 2.58 for a 1 ton shot, and the line (8) does go close to this value.

a



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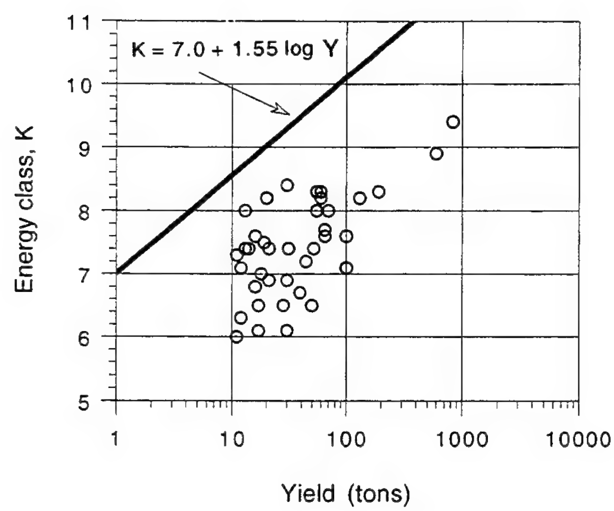
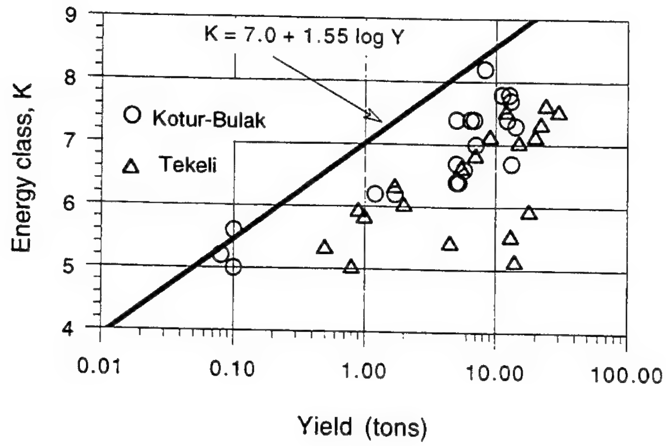


Figure 3 Details of the $K = K(Y)$ data shown for all our data in Figure 2.

a. Mining blasts in Apatity (Kola Peninsula). Energy class K calculated from Mykkeltveit et al.(1992) data. Seismic efficiency of mining blasts in this region is very low: deficit $\Delta K = 3 - 5$ ($\Delta m = 1.4 - 2.3$).

b. Mining blasts in Tyrnauz (North Caucasus) quarries. Seismic efficiency has intermediate value: deficit $\Delta K = 1.5 - 2.5$ ($\Delta m = 0.7 - 1.1$).

c



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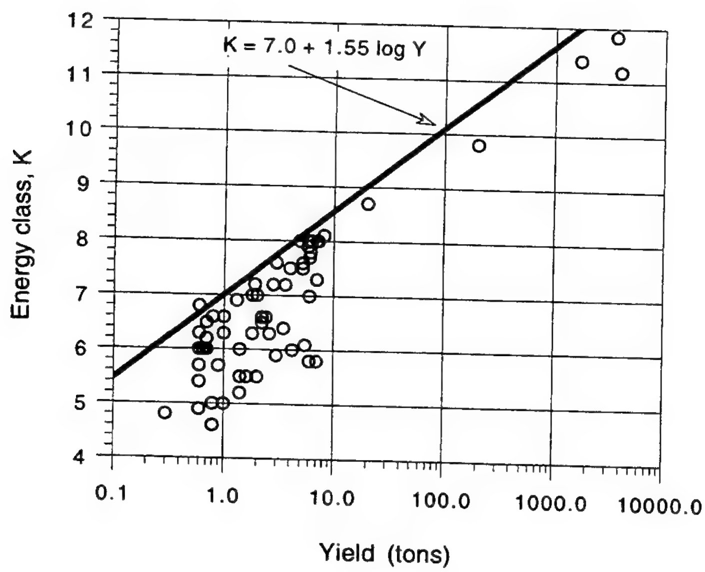


Figure 3 c. Quarry blasts from Kotur-Bulak and Tekeli quarries in the North Tien Shan. Seismic efficiency is high : deficit $\Delta K = 0.5 - 1.5$ ($\Delta m = 0.2 - 0.7$).

d. Quarry and dam-construction explosions in the Medeo region (North Tien-Shan, near Almaty). Observations cover a very wide of yields from 300 kilogram to 3900 tons. Explosions in the Medeo region are characterized by the highest efficiency: deficit $\Delta K = 0 - 1$ ($\Delta m = 0 - 0.45$).

e

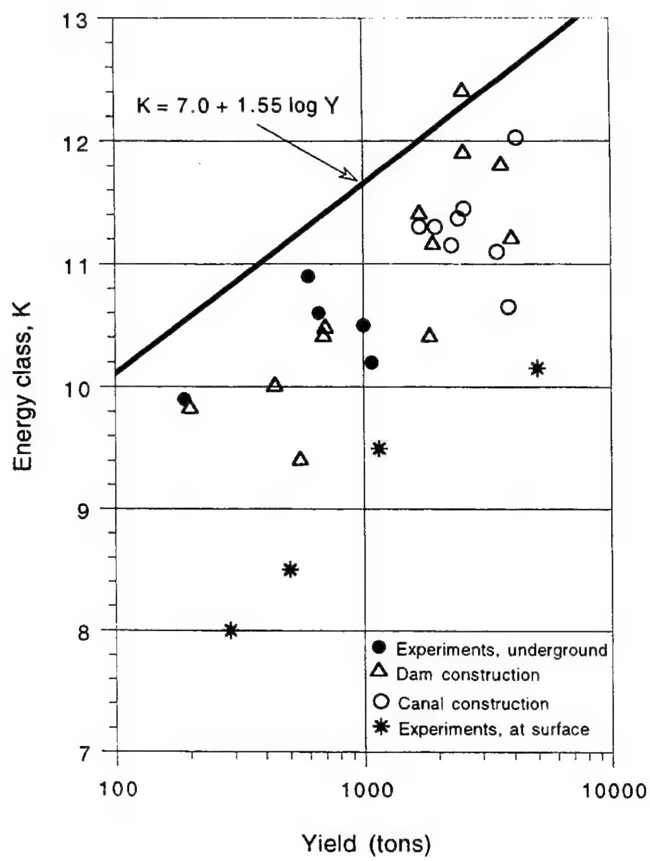


Figure 3 e. Well-documented industrial and experimental underground and surface explosions mostly from Central Asia (see Table 2). Average deficit for surface explosions is $\Delta K = 2.5$ ($\Delta m = 1.1$), and for large industrial explosions $\Delta K = 1$ ($\Delta m = 0.45$).

Some of the detailed features pointed out in Figure 2 are present also in Figure 4. For example, the increase in the magnitude deficit is substantial when going from well-coupled large single-fired explosions, to distributed ripple-fired explosions associated with a different practice of industrial blasting. The deficit increases abruptly by more than one magnitude unit near $Y = 1000$ tons. In Table 4 the magnitude deficit and magnitude and Y intervals are listed for several datasets.

The NPE in Nevada (using m_b from the ISC) has magnitude deficit about 0.6. But if we take into account the difference in attenuation between Nevada and the Kazakh Platform, intensively studied from UNEs at both test sites, a bias correction of about 0.5 magnitude units can be made. See, for example, the magnitude of a one kt explosion predicted by the relationships (1) and (2). The component of the magnitude deficit for the NPE event that is solely due to seismic coupling is therefore quite small. In the same way, a part of the large magnitude deficit for the gold mine explosions in Nevada (as reported by Jarpe et al., 1996) is due to magnitude bias.

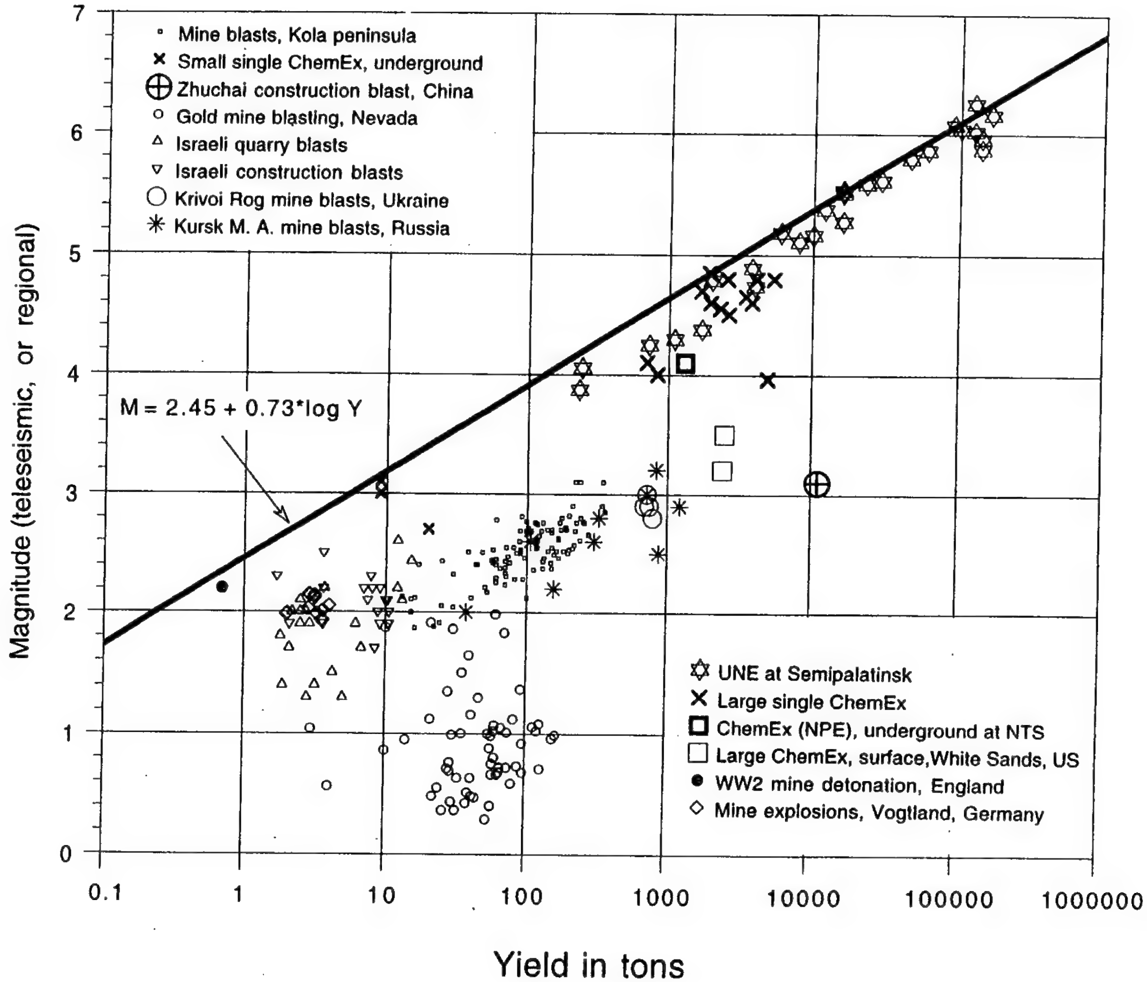


Figure 4. Magnitude versus yield (in tons) for several sets of data. The solid line:

$$M(Y) = 2.45 + 0.73 \log Y \text{ (tons)} = 4.64 + 0.73 \log Y \text{ (kt)}$$

is the upper limit of magnitude vs Y for our observed data. Further details are given in Figure 5. The level of this line is determined by underground nuclear explosions at the Semipalatinsk Test Site, by two well-coupled experimental chemical explosions in northern Kazakhstan, by a mine detonation in England, and also by inference from K values to m_b, for the small Medeo explosions shown in Figure 2. m_b values here are obtained from the International Seismological Centre (ISC) and the British Atomic Weapons Establishment (AWE). Other magnitudes are $m_b(Lg)$ from NORSAR, and regional versions of local magnitude ML and coda magnitude MC.

The explosion in Zhuhai, China, was made to level a hilltop for a new airport near Macow. Its magnitude deficit is 2.3, indicating that its huge charge was probably widely distributed. Though 11200 tons of blasting agent were used, its seismic signals had the same magnitude as each of the 9 ton single-fired chemical explosions in northern Kazakhstan.

Figure 4 includes two single-fired surface explosions in the US, both carried out at the White Sands missile range in New Mexico. Their deficit is around 1.5 magnitude units, due partly to the magnitude bias of the western US and partly to the unconfined nature of these explosions, in which the blasting agent, ammonium nitrate and fuel oil (ANFO), was simply piled up on the ground surface and then detonated to make blast waves in the air.

Table 4. The magnitude deficit Δm for different sets of explosions

Explosions	Figure #	Y, tons min - max	Magnitude min - max	Deficit min - max	Δm aver.
Experimental	5d	9 - 600	2.7 - 4.4	-0.1 - 0.6	0.2
Canal and dam	5d	700 - 4100	3.7 - 4.9	0 - 0.5	0.3
Apatity	5b	10 - 360	1.0 - 3.0	0.9 - 2.2	1.5
Krivoy Rog	5d	680 - 820	2.8 - 3.0	1.5 - 1.7	1.6
Gold Mine, Nevada	5a	3 - 800	0.3 - 2.0	1.2 - 3.4	2.7
Israel	5c	0.8 - 16	0.8 - 2.6	0.3 - 2.0	1.0
Kursk	5d	37 - 1280	2.0 - 3.0	1.5 - 2.4	1.8
New Mexico	4	2000 - 2500	3.2 - 3.5	1.6	1.6
NPE, Nevada	4	1300	4.1	0.6	0.6
China, Zhuhai	4	11120	3.1	2.3	2.3
German mines	4	2.0 - 4.0	1.9 - 2.2	0.6 - 0.8	0.7
UNEs	4	1.7K - 165K	4.5 - 6.25	-0.2 - 0.5	0.2
(nuclear explosions at Semipalatinsk Test Site)					
Underwater:					
Tajikistan	5e	0.32 - 1.28	2.5 - 3.1	-0.45	-0.45
Israel	5e	0.024 - 0.30	2.0 - 3.1	-0.8	-0.8
Ocean	5e	5.5 - 12.7	4.1 - 4.4	-1.2	-1.2

Figure 5 shows some of our magnitude – yield data in more detail. The Apatiti explosions on the Russian Kola Peninsula had local magnitudes *ML* and coda magnitudes *MC* given by Kremenetskaya et al (1995), shown here in Figure 5b. The significant differences apparent

between the two parts of this figure indicate that magnitudes from regional data for small events are sometimes assigned quite different values on different scales. A calibration explosion of 350 tons was carried out on 1996 September 29 in the Khibiny massif on the Kola Peninsula (see Ringdal et al, 1997), and it had a local magnitude $ML = 2.9$ assigned by the regional Russian network. The explosion was in the same region and carried out with the same blasting technique (underground, ripple-fired) as many similar explosions during 1988 – 1993. Their average ML was about 2.55 and yield about 150 tons, so for the 350 ton explosion we would expect ML of about 2.8–2.9, as was indeed obtained locally. The prototype International Data Center assigned ML 3.4 to this explosion, again indicating the need to improve agreement between different types of regional magnitude.

a

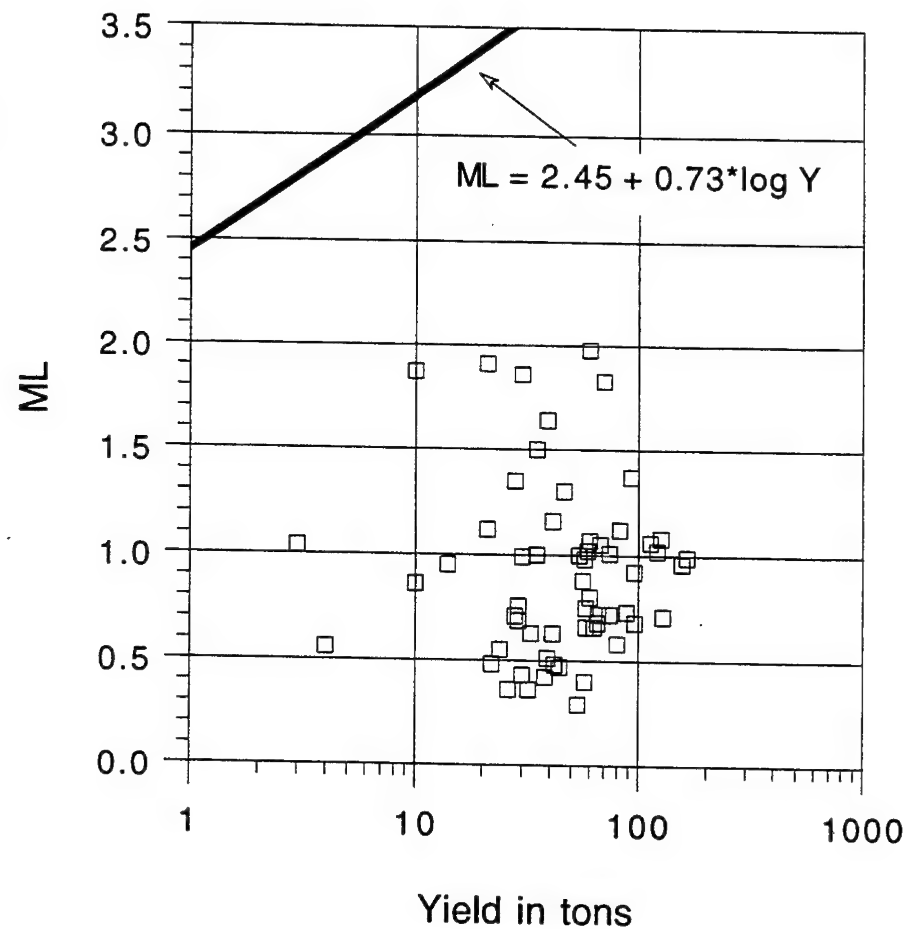


Figure 5 Details of the $M = M(Y)$ data shown for all our data in Figure 4.

a. Mining explosions in an open-pit gold mine, Nevada. Most of these explosions were ripple-fired. Data from S. Jarpe et al. (1996). Explosions in this mine have the lowest seismic coupling efficiency: average $\Delta m = 2.7$.

b

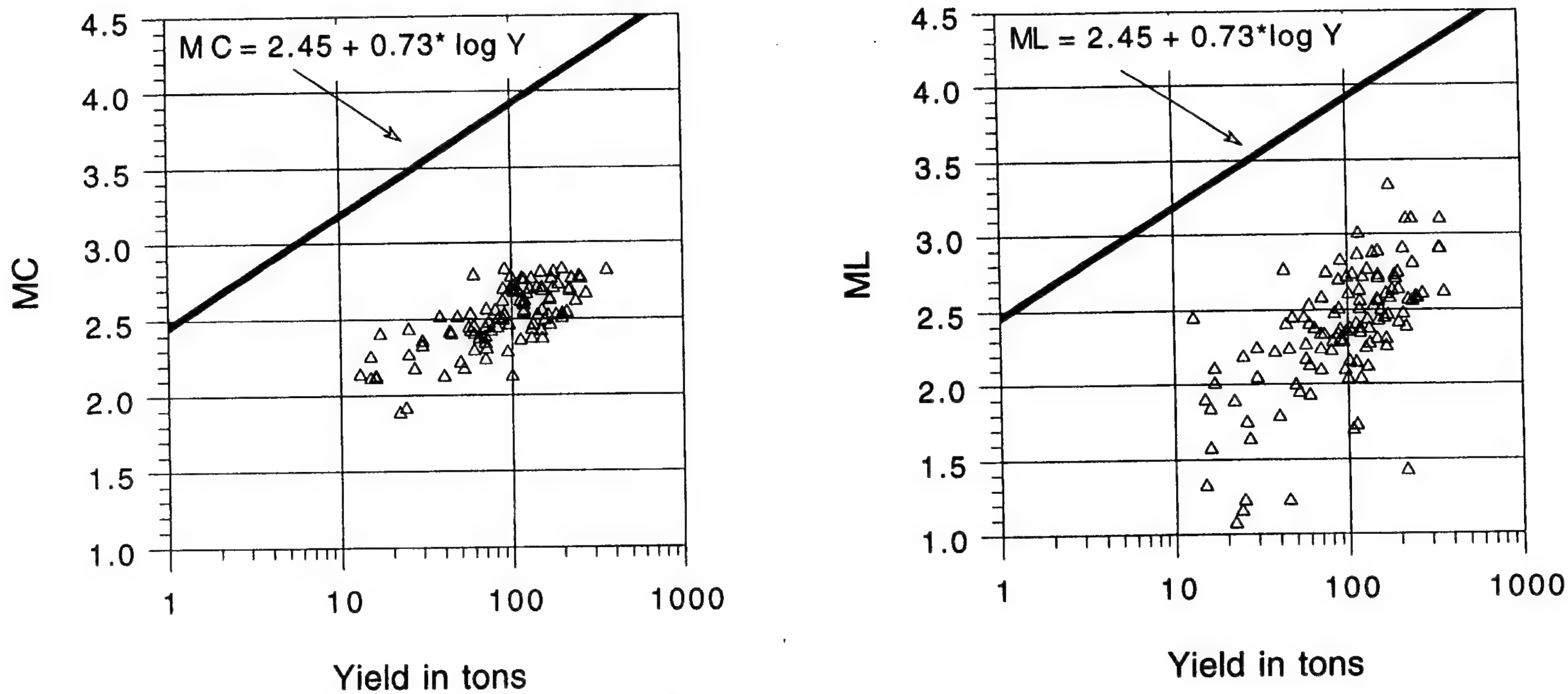
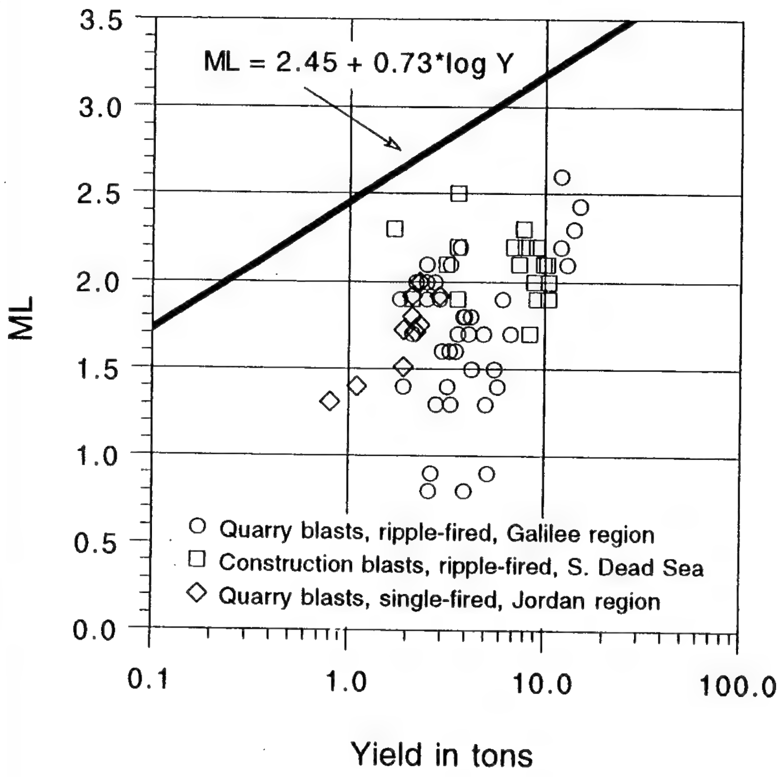


Figure 5 b. Underground mining blasts in Apatity, Kola peninsula, Russia. For these explosions, two types of magnitude were reported: coda *MC* (left) and local magnitude *ML* (right). From Kremenetskaya et al (1995). For *MC* the magnitude deficit is 1.5 and for local magnitude *ML* it is 1.7.

c



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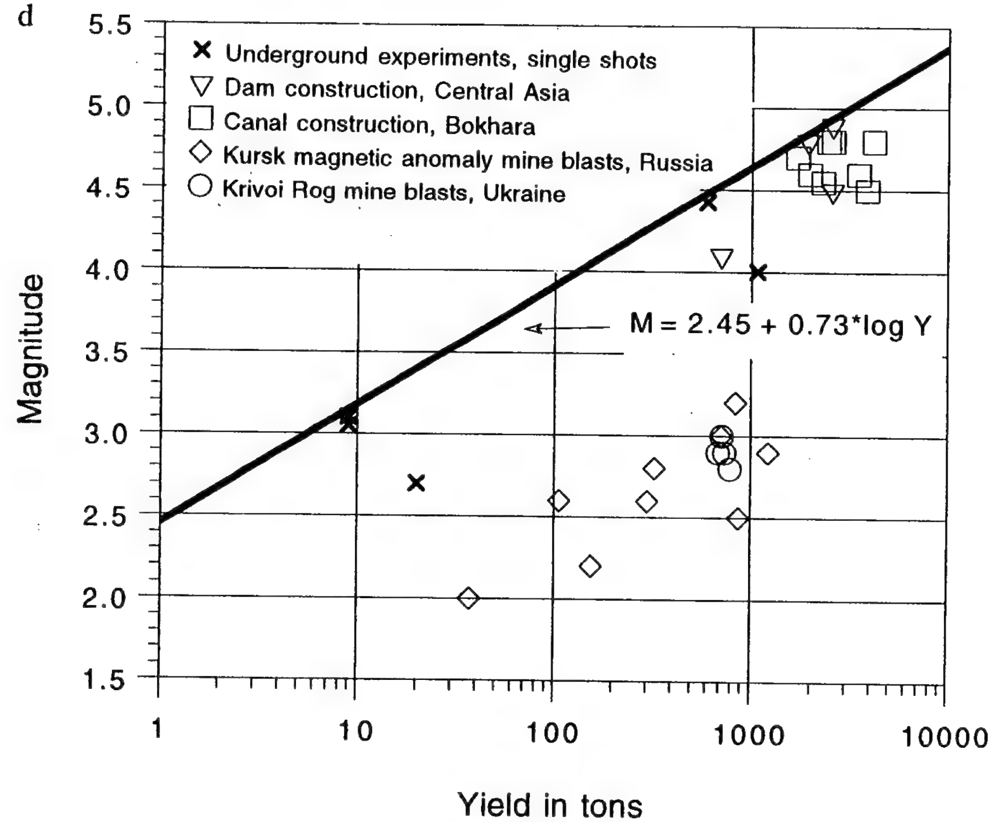

Figure 5 c. Road construction and quarry explosions in Israel. Data from Gitterman et al. (1996). All three types of explosions have nearly the same seismic efficiency: average Δm is 0.8.

d. Large industrial and experimental chemical explosions. Experimental tamped explosions made in northern Kazakhstan have the highest efficiency (Δm is about zero). Mining explosions at the Kursk Magnetic Anomaly have very low coupling efficiency: average Δm is 1.8.

e

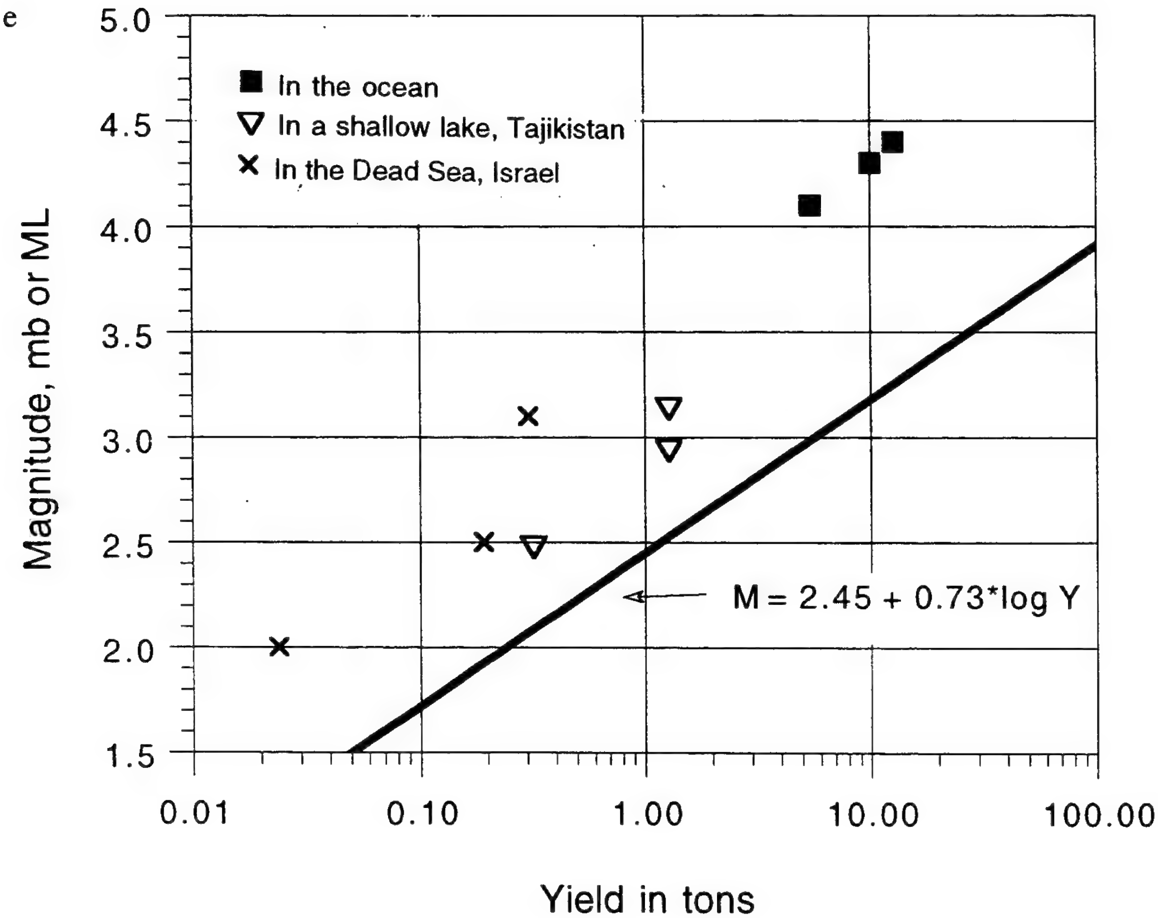

Figure 5 e. Underwater chemical explosions: in the ocean ($|\Delta m| = 1.2$); in shallow lakes (depth 9 – 25 m) in Tajikistan ($|\Delta m| = 0.5$); and in the Dead Sea, Israel, at the depth 70 m ($|\Delta m| = 0.8$). These explosions have magnitude excess, rather than a deficit, because of the super-efficient coupling in water.

The magnitude deficit is from 1 to 2 for large explosions (fired almost simultaneously in long rows) in mines in the Kursk Magnetic Anomaly region (south of Moscow) and at Krivoi Rog (Ukraine). It reaches 2 to 3 for gold mine explosions in the western U.S. (Jarpe et al., 1996) and is much less for small explosions in Israel, carried out in quarries and for road construction (Gitterman et al, 1993 & 1996). The magnitude deficit for the shots in Israel is 0.1 to 1.5.

Finally in this section, we point out the super-efficient seismic coupling of shots carried out

underwater. Figure 5e shows several examples, with magnitude excesses in the range 0.5 to 2. Data for the shots in Israel are from Gitterman et al (1996); for the shots in the ocean (20 Aug 1970, 20 Jul 1971, 11 Jun 1972) are from the ISC (see also Jacob and Willmore, 1972); and for the shots in Tadjikistan are from Gamburtsev et al (1996). The coupling efficiency of underwater explosions has long been exploited to provide sources for seismic refraction surveys, where the source is usually chosen to maximize signal strength using blasting practices that have minimal cost. Murphy (1996) has shown that peaceful nuclear explosions carried out by the Soviet Union in clay also have higher magnitudes than the same yield fired in hard rock.

DISCUSSION

The size of a chemical explosion is expressed commonly in terms of its total charge. But it is important also to investigate explosion size in terms of seismic magnitude, whether local, regional, or teleseismic, when the principal concern is with the *observability* of blasting activity. To this end we have defined the concept of seismic magnitude deficit, being the amount by which signals are smaller than expected for maximum seismic coupling in hard rock, under conditions of efficient seismic wave propagation, and at the same yield as the explosion whose deficit we wish to estimate.

It is apparent from the data we have presented that the magnitude deficit of a chemical explosion is due to a number of contributing effects. We can write

$$\Delta m = \Delta m_{\text{blasting practice}} + \Delta m_{\text{geologic medium at the shot point}} + \Delta m_{\text{region}}. \tag{9}$$

Thus, blasting practice has an influence because it matters whether the shot is well tamped or not, whether it is deep or shallow or at the surface, and whether it is ripple-fired or single-fired. The geologic medium at the point of emplacement has an influence (see, e.g., Denny and Johnson, 1991). And the effect of different regions is seen, in the way that attenuation can vary for different paths of propagation to the reporting stations. Each of these contributing factors has been studied extensively.

Of particular interest in the context of CTBT monitoring, are any explosions in which large amounts of explosive or blasting agent are fired all at once in a contained environment. A few decades ago it was common practice in certain mines and quarries in the U.S. to drive a tunnel into a rock face, to fill the tunnel with chemical explosive, and to fire the whole charge at once. This practice is called *coyote blasting* in the U.S. (The name arose, because sometimes it was possible for blasters to find an existing tunnel, such as a coyote might be using.) The idea was to lift the body of rock upwards and sideways above the tunnel, so that the rock was fragmented as it fell back down. This practice is known to produce strong seismic signals, since, when carried out correctly, the explosion is substantially contained. But coyote blasting is a notoriously dangerous practice because of the possibilities for miscalculation: too much charge and the explosion will blow fragments far and wide; too little and the rock does not fragment as desired.

The following are Richards' notes of a January 1994 interview with an expert old-time blaster, who executed many coyote blasts in the 1950's and 1960's:

> "The Corona quarry in Southern California shot coyote blasts up to a million pounds in the 1950's... The Mapleton quarry, Pennsylvania, shot coyote blasts around 25–30,000 pounds until recently... The key is, to break the rock up small enough so it's easy to move. You could get a lot of rock for little money—but [coyote blasting] is a lawyer's delight today. The only place I know where it is still carried out regularly, is blasting in basalt in Oregon and Washington - maybe several thousand pounds at a time—to break rock used for logging roads."

Seismic data from the network operated by the University of Washington confirms that some of the seismicity observed in logging areas appears to be due to blasting (personal communication, S. Malone).

The practical reason it has become possible to avoid the dangers of coyote blasting, is that drilling technology has improved so much in recent years. For the typical large chemical explosions now carried out for commercial purposes, ripple-firing with a sequence of preplanned delays is used exclusively. This conclusion is reached after interviews with numerous blasters, blast vibration consultants, and powder company executives.

The technology of blasting has become more and more sophisticated in recent years, with increasing reliance on accurate timing to achieve maximum desired fragmentation in a controlled blast. The mining industry now refers to high-tech ripple-firing as "millisecond delay initiation."

The common purpose underlying almost all industrial blasting is to break or move rock. Often the goal is to break the rock into fragments of prespecified size.

The amount of ground vibration is found in practice to be related to the maximum size of charge fired in any hole, rather than to the total charge size (Devine and Duvall, 1963; Nicholls et al, 1971). It appears that the seismic magnitude is also determined by the amount of charge detonated in one component blast, which for a large industrial explosion will be on the order of 1% of the total—contributing 2 magnitude units to the deficit, according to (9). Thus, blasts of over a kiloton in Wyoming surface coal mines are observed to have magnitude around 2 (personal communication, L.Glenn), whereas they would be expected to have magnitude around 4 for a contained kiloton fired all at once.

Another type of blasting with effectively instantaneous detonations is presplit blasting, in which a single line of holes are lightly charged and all are fired together. The purpose of presplitting is to propagate a crack between holes to establish a fracture plane in the rock mass—for example, around the perimeter of a future excavation site, so that the finished face of the rock, left after the excavation has been completed, is smooth and undamaged. But since the intent is not to fragment the rock, presplit blasts do not use large amounts of explosive.

Blasting practices in the U.S. in surface mining for coal underwent significant changes following 1986, when the Surface Mining Act prompted a series of regulations (30 CFR, paragraphs 816.61 to 816.67). These changes included rules governing how much explosive may be shot in any 8 ms period. As a result, the "maximum pounds per delay period" is now *defined* in U.S. industry to be the amount of explosives designed to be detonated within an 8 ms interval.

Blasting is also highly regulated in West European countries. Even where there is little or no regulation, blasting in practice is carried out with ever-increasing attention to the smooth working of operations around the blast site. For example, in an open pit copper mine or a strip-mining operation where millions of dollars of equipment must be used efficiently for commercial success, it is undesirable to stop operations for any length of time and pull equipment back from the vicinity of a blast site. The blasting industry in the U.S. (and presumably elsewhere) is still undergoing changes in professional practice, adopting more sophisticated techniques to minimize ground vibrations and maximize the intended function of the blast—which, again, is almost always to break rock safely and reliably into fragments of a chosen size. The outcome of these changing techniques in the U.S. has been a reduction, over a period of several years, in the magnitude of seismic motion associated with blasting activity.

To summarize the above discussion of changes in blasting practice, almost all aspects of industrial blasting in the U.S. emphasize techniques that are different from that associated with execution of a deep, large (over 100 tons), single-fired chemical explosion, such as the Non-Proliferation experiment of September 1993 or the Soviet-era chemical explosions of the 1950's and 1960's. The latter type of underground explosion is an inefficient way to break rock, and the most efficient way to make seismic signals.

(9) has a regional term, contributing to the deficit. Regional differences are often associated with the need for station magnitude corrections when interpreting teleseismic m_b. But in practice, when all the major factors affecting the deficit are contributing together, we can use the deficit to characterize directly the cumulative outcome on chemical explosion magnitudes.

In some regions the seismic efficiency of explosions can be high for local observations (ML) and low for teleseismic m_b. Such a disparity may apply to the Lake Baykal region, with a high Q crust and a low Q upper mantle. In this region, mining and quarrying are carried out extensively with many seismic observations of regional waves, but without teleseismic detections.

At the beginning of our study we were not sure whether the upper limit $M = M(Y)_{\max}$ for chemical and nuclear explosions would be the same. It is commonly thought that under the same conditions of containment, depth and shot point geology the seismic signals from a chemical kiloton are about twice those of a nuclear kiloton (see, for example, Denny et al, 1996). Only after examination of available data in the region of yields where we had both chemical and nuclear explosions (230 to 4000 tons) did we conclude that the upper limit and hence the maximum seismic efficiency is essentially the same for both groups. The level of the upper limit curve has applicability beyond our own interests. For example it can indicate the source size needed in a long-range refraction survey.

Mine blasts in the Kuzbass region, to the east of Novosibirsk in western Siberia, have a deficit amounting perhaps to about 0.65 magnitude units (see Table 3), but we are aware that explosions in this region (and in the Abakan region slightly further to the east) have often exceeded $K = 10$, which corresponds approximately to magnitude 4 via (3). These explosions are often detected by regional stations out to 1000 km in Central Asia (personal communication, W.-Y. Kim) and possibly at teleseismic stations. The Kuzbass/Abakan region appears to contain some of

the largest mine blasting operations (in terms of seismic magnitude and frequency of signals) in Eurasia. As such, the region will be of interest to those who must interpret the Kuzbass blasting signals that will surely be recorded by seismographic networks used to monitor compliance with the Comprehensive Test Ban Treaty.

It is of interest that the magnitude-yield relation of Ringdal et al (1992), derived for the underground nuclear explosions at the Semipalatinsk Test Site, differs very little from our relation between the maximum magnitude and yield—compare (1) and (8). In our terminology, the deficit of these nuclear explosions is only about 0.15 magnitude units.

CONCLUSIONS

We have found the upper limit on magnitude as a function of yield, for chemical and nuclear explosions in hard rock.

We have defined the deficit of an explosion as the amount by which its seismic signals are smaller than would be expected if the explosion were carried out under most favorable coupling conditions in hard rock, and with most efficient propagation characteristics. The deficit is a quantitative measure of the inefficiency of generation of seismic signals. We find that the magnitude deficit is typically around 1.5 to 2 magnitude units for chemical explosions in the mining and construction industries. This is the reason that the great majority of blasts that would be counted as large in terms of charge size, are in fact not detected seismically. The reason for the inefficiency of generating seismic signal, is presumably because the usual commercial purpose of chemical explosions entails the need to fracture rock into small pieces—which necessitates firing practices (such as ripple-firing) in which much of the explosive energy goes into rock fragmentation. A smaller fraction is then radiated seismically, than would be the case for a well-tamped single-fired shot.

In the context of treaty monitoring it is fortunate that the great majority of mining areas do not conduct blasts with seismic signals of magnitude above 3, and very few (on the order of ten per year in the U.S.) are associated with signals above magnitude 3.5 (see Part 2 of this Report). Nevertheless there are a limited number of regions in which mine blasting is seismically detectable over large distances. The Kuzbass mining region of W. Siberia, Russia, and the region near Abakan further to the east, appears to be associated with explosions with magnitude greater than 3.5 that are likely to be detected a few times each month at considerable distances.

Also in the context of treaty monitoring, and for general seismological studies of chemical explosions, it will be very helpful to improve upon current practices of assigning magnitude based upon regional signals, and then to relate regional magnitudes for small earthquakes and explosions to magnitude values assigned on the teleseismic m_b scale.

ACKNOWLEDGEMENTS

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Part 2 of this Final Report consists of the following paper, prepared for submission to the Bulletin of the Seismological Society of America in January 1998:

MAGNITUDE DISTRIBUTIONS OF MINE BLASTING ACTIVITY IN DIFFERENT REGIONS

Vitaly I. Khalturin, Tatyana G. Rautian and Paul G. Richards[1]
Lamont-Doherty Earth Observatory of Columbia University
Palisades, NY 10964
([1]also, Department of Earth and Environmental Sciences, Columbia University)

ABSTRACT

We have obtained data on regional magnitude for several thousands of chemical explosions in more than 30 mining regions worldwide, and have used these data to provide summaries of the numbers of chemical explosions likely to be of interest in monitoring compliance with the Comprehensive Test Ban Treaty. Much of our data are for mining regions on territory of the former Soviet Union, but we have also obtained summary information for the Czech and Slovak Republics, Southern France, Germany, Israel, Poland, Scandinavia, Syria, and the United States.

We find that few mining regions carry out blasting associated with seismic signals above magnitude 3.5. The actual number of such regions depends upon details of how magnitude is assigned. In the United States, it appears there are on the order of 10 mining blasts per year with magnitude greater than about 3.5. In Russia, there are on the order of 100 blasts per year with magnitude greater than about 3.5. The region in Russia with the strongest seismic signals from mine blasting is the Altai-Sayan, associated with the Kuzbass and Abakan mining regions in Western Siberia.

We also find that the slope of the frequency-magnitude relation is typically much steeper for mine blasting signals, than for earthquakes; and thus that large numbers of mine blasts (hundreds per year) occur at magnitude 3 and lower.

INTRODUCTION

This paper provides estimates of the numbers of mining blasts likely to occur in different regions, at different magnitude levels. Though there is some seismological interest in mine-blast signals for studies of crustal structure, the principal motivation for our work is to assist in the evaluation of a practical problem that may arise in the context of developing the verification regime for a Comprehensive Test Ban Treaty (CTBT).

The practical problem is that efforts to provide high quality seismic data for discriminating earthquakes from underground nuclear explosions, even at small yield, will inevitably result in the detection of numerous small underground chemical explosions. It is often more difficult to discriminate between underground chemical explosions and underground nuclear explosions (using the combined signals derived from seismology, infrasound, and radionuclides), than to discriminate between earthquakes and explosions. Hence, there is a need to know how many chemical explosions (mostly mining blasts) may be expected to occur, that would give rise to signals large enough to be credible candidates for suspicion as originating from a nuclear explosion.

Mining is an activity often associated with uses of sophisticated drilling and earth-moving equipment, and therefore conceptually may provide a plausible environment for evasion of CTBT constraints, at least for underground testing. For example, conceptually a small fully-decoupled underground nuclear explosion might be carried out in a mine at the same time as a large routine chemical blast in the same general location. Or, conceptually, a nuclear shot might be carried out alone, and reported to inquirers as a chemical explosion.

It is only in the context of the greatly improved detection capability associated with various reporting networks in recent years, and concern with evasion scenarios such as those traditionally associated with decoupling and thus the need to monitor at low magnitude, that seismic signals associated with blasting activity are potentially problematic. It is therefore relevant to recall the history of how requirements for CTBT monitoring have evolved. Only with such a background, which shows that monitoring standards have changed greatly since CTBTs were first discussed, can potential problems associated with blasting practices of the mining industry be placed in perspective.

The Limited Test Ban Treaty (LTBT) of 1963 was preceded by about five years of intense efforts to negotiate a CTBT, and by intense efforts over the same period to consider how the occurrence of underground nuclear explosions might be detected and identified (Richards and Zavales, 1996). The U.S. requirements for seismic monitoring in the last stage of negotiations in 1963, in support of a trilateral CTBT between the U.S., the U.S.S.R., and the U.K., were essentially to have a detection capability down to about magnitude 4 for the Soviet Union; and identification capability for enough of the events in this region above magnitude 4.75, so that for the remaining unidentified events (above magnitude 4.75) a program of on-site inspection (OSI) could be relied upon (U.S. Congress, 1963).

At the time, magnitude 4.75 was thought to represent about 19 kilotons (by extrapolation using experience with the 1957 shot RAINIER at the Nevada Test Site). Those early CTBT negotiations failed, ostensibly over the number of OSIs that would be allowed. The inability in 1963 to demonstrate convincingly that identification capability was attainable down to magnitude 4.75 contributed strongly to the decision not to ban underground testing in what then became the LTBT (the "atmospheric test ban treaty"), and hence to underground test programs in the period 1963 to 1996. (The last underground nuclear test carried out by the Soviet Union was in 1990; that by the United States in 1992. The last tests by France and China were both in 1996.)

In the 1960's, chemical explosions were deemed far too small to be of interest in treaty monitoring, since, except for accidents or very unusual construction shots, they did not (and still do not) occur with signals even approaching magnitude 4.75.

It has been apparent since the early 1970's that seismic data are in fact adequate to achieve identification down to well below magnitude 4.75 for Eurasia, and probably for the rest of the world, without the need for OSIs. And identification is even better with respect to a 19 kiloton reference, since for most of the Soviet Union the expert community in western countries began to realize in the late 1970's that magnitude 4.75 corresponds to only 2 – 3 kilotons. However, the standards for effective verification have become much more stringent than was the case in the 1960's. For example, the network of seismometers under construction in the 1990's for the international verification regime is expected to provide data permitting event identification down to around magnitude 4 or below for Eurasia; and thousands of additional seismic stations distributed around the world can potentially be drawn upon to achieve even better capabilities in some regions.

It will be desirable to develop routine discrimination procedures that can identify events down into the magnitude range 3 – 3.5, thus reducing the number of detected but unidentified events to a level that is deemed manageable, even at magnitudes way below what was thought relevant in the 1960's. Signals of such low magnitude, if caused by underground nuclear explosions, could arise only from shots with yield on the order of 40 – 100 tons if tamped in hard rock; or conceptually from yields of a few kilotons if the shot were carried out as a major effort in decoupling (with attendant problems of how to contain radionuclides).

The remaining sections of this paper present our data on the magnitude distribution of mine blasting in different regions, followed by discussion and conclusions. We find that very few regions have blasts larger than magnitude 3.5, but that many regions carry out blasts with magnitudes in the range 2.5 to 3. The slope of the frequency-magnitude relation is much steeper for mine blasting, than for earthquakes (the *b*-value is around unity for earthquakes but typically greater than 2 for blasting). This latter result is good from the perspective of concern over very large blasts—because it implies there are very few such events. It also indicates that the number of blast signals rises rapidly with decreasing magnitude, as one considers events significantly smaller than the largest events in a given region.

DATA

For different mining regions, we have sought information on the charge size (the total of all sub-charges or "delays"), and the seismic magnitude of signals generated by blasting operations. To date we have acquired 13 examples of the way in which charge size, Y (in tons of blasting agent), is distributed; and 33 examples of the distribution of magnitude. Most of our examples illustrate the distribution of magnitudes (or charge size) for mining operations at different locations; but some of our examples are selected to see if magnitudes and charge sizes have changed with time in the same mining region.

We have usually worked with explosions too small to be detected at teleseismic distances, and therefore we have used regional magnitudes such as *MC* (based upon coda, and typically taking the form of a measurement of signal duration), or *ML* (a local magnitude, based upon the largest amplitude in a recorded signal).

Our data on seismic signal strength in many cases come from measurement of the energy class, K. It was important to include such data, because they are the only measurements of seismic signal strength reported for many explosions (and earthquakes) on territory of the former Soviet Union. The K scale (Rautian, 1960) has been in use since the late 1950's up to the present time to characterize the size of locally- and regionally-recorded events at distances from a few km up to 2000 km. K is based upon the sum of amplitudes A_p and A_s of both P and S (or Lg) waves on short-period instruments, together with a distance correction to turn the measurement of signal strength into an estimate of size of the seismic source. K is called a measure of the energy class, because it is an estimate of the value of log E, where E (in joules) is the seismic energy radiated by the source. An increment of K by one unit corresponds to an increment of $\log(A_p + A_s)$ by 0.56 units.

Khalturin et al (1998) showed for both chemical and nuclear explosion data that there is a simple linear relationship between energy class K and teleseismic magnitude m_b, taking the form

$$m_b = 0.46\ K - 0.64. \tag{1}$$

Therefore, in order to present all our results on the magnitude-frequency relation in a standard way in this paper, we have chosen to convert all K values in our datasets to magnitude, using (1). For such magnitude values based upon K, we use the symbol *MK* throughout this paper. *MK* is therefore a regional magnitude scale, which is tied to teleseismic magnitudes.

The distribution of mine blast magnitudes can be described, at least for a small range of magnitudes M of interest, in terms of a linear relationship that is fit to the actual $N = N(M)$ data:

$$\log N = a - b\ M. \tag{2}$$

$N = N(M)$ here is the cumulative number of events, having magnitude greater or equal to M. The a value is related to the total number of explosions occurring over a given magnitude range, for the time interval of the dataset. The slope, $-b$, also depends in practice upon the magnitude

scale used, but is independent of the time interval if seismicity rates do not change with time. For earthquakes, the value of b is about 1 if the magnitude scale is m_b. For the Russian regional scale (energy class K), the average slope is known to be –0.43 for earthquakes. Since we often use the MK scale in this paper, applied to mine blast data, it follows from (1) that

$$d(\log N)/d(MK) = 2.2\ d(\log K)/dK \tag{3}$$

so that, by definition of MK, the slope for $N(MK)$ is 2.2 times the slope for $N(K)$, on log–linear plots. The main reason for discussing the frequency-magnitude relation for mine blasts in terms of (2), is to draw parallels with experience gained from using the frequency-magnitude relation for earthquakes. For earthquakes, (2) is commonly found to be a good fit to data for seismically active regions in which complete coverage is available over the magnitude range of interest.

For the distribution of yields we can similarly try to fit cumulative $N = N(Y)$ data with a linear relationship between N and charge size (or, yield) Y, in the form

$$\log N = c - d \log Y. \tag{4}$$

We now turn to a presentation of our data, in which $N = N(Y)$ and $N = N(M)$ are compared in each case with a straight line of the form (2) or (4). Obviously we use (4) where we have data on charge size, and (2) where we have magnitude data. A later section comments on the fact that the slopes of our straight line fits are typically much steeper than the unit slope associated with earthquake magnitude distributions. Also, the reason for the fall-off at low magnitudes is often different, between mine blasts and earthquakes.

Figures 1 to 13 show the distribution of log Y values for 13 different mining operations. Each figure indicates the name of the mine or mining region, the number of months for which we have data, the mine location, and the parameters of a linear fit of the form (4) for the larger explosions. The Y-axis has the same scale (from 1 to 1000 tons) for Figures 1 to 12, but is different for Figure 13 (there ranging from 1 to 10000 tons).

Figures 14 to 45 show the distribution of magnitude values for 32 different mining operations. Each figure indicates the name of the mine or mining region, the number of months for which we have data, the mine location, and the parameters of a linear fit of the form (2) for the larger explosions. The magnitude axis covers the same range (from 1 to 5) in all these Figures.

All data exhibit the same general characteristic of a steeper slope for the higher magnitudes. Since the larger events will be of greater concern in the context of CTBT monitoring, in each case we have chosen to fit a linear relationship, either (2) or (4), to these larger, but fewer, events.

Some comments on the particular features of different mining regions are noted in the figure captions. Before discussing our overall results on the frequency-magnitude relation, we comment on what is known about mining seismicity in the United States.

Distribution of magnitudes, for U.S .mining seismicity

About two megatons of chemical explosives are used annually in the U.S., principally in mining for coal and metal ores. Most of this explosive is used in surface mines rather than underground mines. On a typical work day there are about 30 explosions greater than 50 tons, including one shot greater than 200 tons (Richards et al, 1992). Shots greater than a kiloton are carried out routinely in the Powder River Basin of Wyoming and Montana. Shots greater than 100 tons are thought of as large by the blasting industry and occur only at a limited number of mining operations. Shots in underground mines are typically much smaller, because of safety considerations. Almost all chemical explosions above 1 ton in the U.S. are ripple-fired and almost all above 10 tons are also shallow. Almost all are intended to break rock or to remove overburden, and are therefore very inefficient, relative to contained single shots, in generating seismic signals at regional or teleseismic distances.

The above information on numbers of explosions with charge size more than 50 tons would seem to indicate a problem with CTBT monitoring, if it were correct to interpret such levels of blasting activity with a magnitude-yield relation typical of underground nuclear explosions, since such a relation would then predict that hundreds of mine blasts each year would have magnitude greater than 4.5, and thousands would have magnitude in the range 3.5 to 4.5. However, information on basic statistics of mining seismicity that has begun to emerge in the United States shows that such predictions are wrong, and that only a few tens of mine blasts occur per year at the magnitude-3.5-and-above level, rather that thousands.

For many years, the National Earthquake Information Service of the US Geological Survey (USGS) has routinely located earthquakes and has published the resulting seismicity information in a variety of different bulletins. The underlying purpose of these bulletins is to assist in the documentation of earthquake hazard and the scientific study of tectonics and earthquake sources, so mining seismicity has routinely been excluded. However, the work of monitoring compliance with the Comprehensive Test Ban Treaty has lead to the need for information on mining blasting and mining seismicity. Indeed, in Part III of the CTBT Protocol, a series of confidence-building measures is listed concerning chemical explosions, the main feature being the voluntary provision by each State Party, of information about chemical explosions conducted on its territory that have 300 tonnes, or more, of TNT-equivalent blasting material. Therefore, beginning in 1997, the USGS began to process seismic signals from mine blasting and from mine-induced events such as rockbursts, rather than rejecting them as had previously been the practice. The USGS analysis started with May 1 of 1997, and is essentially the same as that used in standard procedures of analysing seismic phases to locate earthquakes and to assign magnitude. The events associated with mining are now diverted to a new bulletin of mining seismicity. The URL for this new bulletin is http://earthquake.usgs.gov/neis/mineblast/.

For the six-month period from May 1 to October 31, 1997, the new USGS bulletin of mining seismicity, as of early December 1997, had located 886 events, of which 821 were also assigned a magnitude (typically, *ML*). The magnitude distribution is shown in Figure 46. In this

six-month period, two blasts had the largest reported magnitude of 3.6 (one in Ohio, one in Kentucky). The next largest signals were at magnitude 3.4, from eight events (one in Ohio, one in Wyoming's Powder River Basin, and six in West Virginia—one of which was a possible rockburst, and another a probable rockburst). A line with slope −2.3 is shown in Figure 46, indicating that the fall-off in the distribution with increasing magnitude is quite steep (compared with the slope of around −1 usually seen for earthquakes). Figure 47 shows the spatial distribution of the 821 events—indicating widespread mining activity in the western states, and concentrated activity in Kentucky, Tennessee, Ohio and West Virginia. Figure 48 shows the number of events per hour, centered on the GMT hour of the day. It is apparent that standard working hours in the U.S. cover more than 90% of the times at which blasting occurs.

In addition to the information now available from the USGS and reported in Figures 46 – 48, a survey of how many mine blasts are detected at several U.S. regional networks was reported by Richards (1995). In the U.S., there are on the order of a few (one to three) chemical explosions a month reported as being above regional magnitude 3.4; however, it is probable that these shots typically have lower magnitudes on a teleseismic magnitude scale (which is the more relevant scale for characterizing the seismic signals from a nuclear explosion). There are perhaps hundreds of shots in the U.S. each week above local magnitude 2.5. For many regions where a seismographic network exists that can detect all events down to magnitude 2, it is common to find that signals are picked up from far more chemical explosions than earthquakes.

Finally, in this section on U.S. mine blasting, it is relevant to comment on another type of chemical explosion as typified by the Non-Proliferation Explosion (NPE) conducted at the Nevada Test Site on September 22, 1993. This special explosion was large (~1000 tons), deep and contained, and single-fired. While these properties make the NPE similar, in seismic excitation, to a small underground nuclear explosion, they also make the NPE unique among chemical explosions in recent years and certainly non-representative of industrial blasting. Explosions with the characteristics of the NPE serve no commercial purpose. If and when such special explosions are conducted in future, the voluntary procedures spelled out in the CTBT Protocol may prove especially valuable in allaying any concerns of CTBT violation.

DISCUSSION AND CONCLUSIONS

First, we note that our results are intended only as indicating general features of magnitude distributions for mine blasting, rather than being specific with a high degree of accuracy. The main reason that so many of our numbers are still somewhat uncertain, is that many different regional magnitude scales are in common use, without serious efforts to reach agreement on the relationship between different scales. With this caveat, we can go on to point out our general results.

The difference in slopes (*b*-values), between earthquake and explosion data, has important implications for the monitoring problem. The fact that slopes of log N vs. magnitude are typically much steeper than the −1 value typical of earthquakes, is associated with the reality that there is cut-off in magnitude for mine blasting in a particular region. The steeper the slope, the sharper the cut-off. However, although the steep slopes provide one way of quantifying the small numbers of

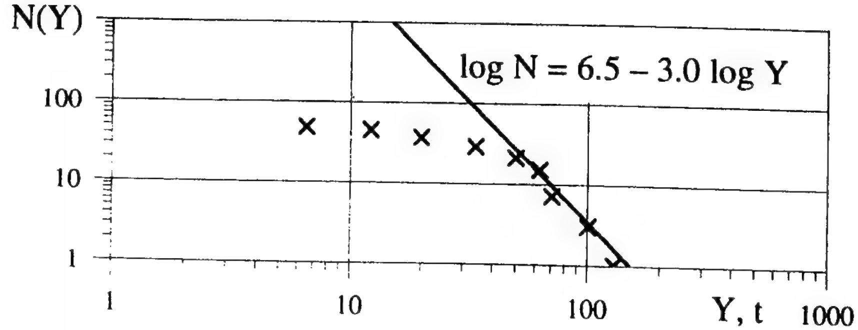
mine blasts at high magnitude, they also lead to the conclusion that the numbers of low magnitude mine-blasting events can increase greatly with decreasing magnitude.

For earthquakes, the fall-off to a lower slope at lower magnitudes is usually taken as an indication of failure to include, in the total dataset, all the events that actually occurred at the lower magnitudes. But for our mine blast data, although there are surely examples where the lower magnitude events were not all detected for inclusion in the dataset, it is likely that the flattening is a consequence of typical blasting practice for the region being studied. For example, it is common for a mine to use a standard charge size for a particular type of operation such as removal of overburden, or fragmentation of ore for later processing. If most blasts occur with roughly similar magnitude in a particular mining operation, but with some scatter, then the cumulative magnitude-frequency relation will indeed flatten at lower magnitude. For such cases there is little if any physical significance, in the steep slope at higher magnitudes. It is however still of some use to estimate the slope, since from the monitoring perspective it quantifies the rate at which the number of detectable blasting signals will increase with decreasing magnitude, when those signals are detected for a particular mining region by a particular network. In a region where both earthquakes and mine blasts are recorded, the earthquakes will usually dominate at higher magnitudes, and also at very low magnitudes (though such small earthquake signals may not be recorded); but there may be a range of low magnitudes within which mine blasts provide most of the detected signals. Such dominance of regional seismicity by mine blasting is well-known in the U.S. for stations in and near Kentucky, Tennessee, West Virginia and Ohio.

From Figures 39 and 34 – 38, the Kuzbass mining region of the Altai and the Abakan mining region of the Sayan (both in Western Siberia) stand out in terms of the numbers of explosions, and the size of the largest explosions. These Figures show for the two regions taken together that on the order of 100 to 200 mine blasts occur in Western Siberia each year with magnitude 3.5 and larger; and that about 2 blasts per year have magnitude 4 and larger. These annual rates appear not to have changed significantly over the last several years, though they presumably would change if mines in this region adopted more modern blasting procedures, in which larger numbers of smaller delays are used for the same total charge size in each blast. The current style of blasting in Western Siberia is likely to result in routinely reported events on almost a daily basis at the CTBT International Data Centre, once the network of monitoring stations reporting to the IDC approaches completion in Southern Russia, Siberia and Central Asia. We know of no other mining region having such high numbers of blasts, at magnitudes large enough to be likely to result in routine reporting by the CTBT IDC, and large enough to overlap with the magnitudes of small underground nuclear explosions.

For purposes of routinely discriminating between large mine blast signals and signals from an underground nuclear explosion, we anticipate that a very useful role may be played by sensors of infrasound and radionuclides. With other seismologists, we are planning a program of research to investigate the combined uses of infrasound and seismic signals, to see if the large mine blasts

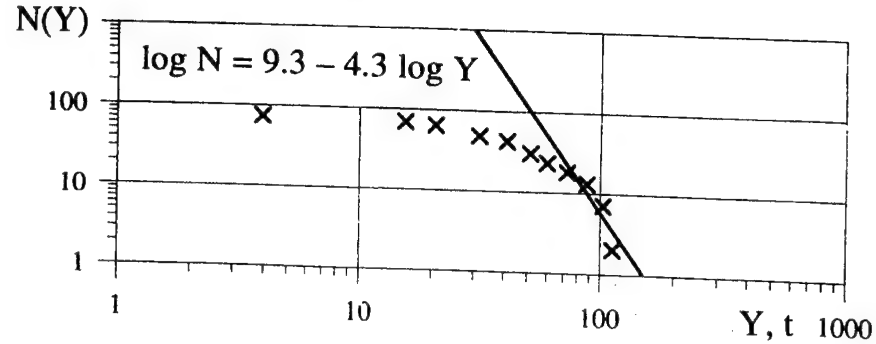
Azey; 4 months



one mine, Baikal region ; Jun 1992-Sep 1992

Figure 1

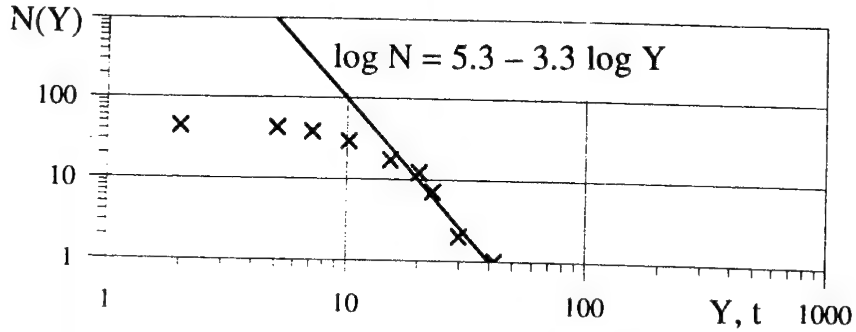
Cheremkhovo; 14 months



53.22 N; 103.1 E ; Jul 1991-Sep 1992

Figure 2

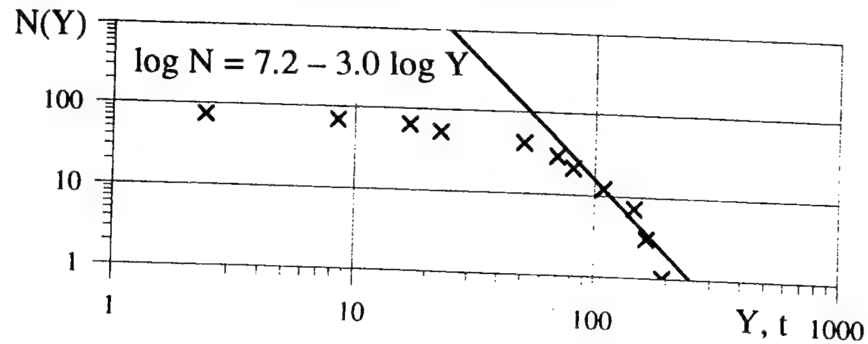
Tulun; 15 months



54.6 N; 100.5 E ; Jul 1991-Oct 1992

Figure 3

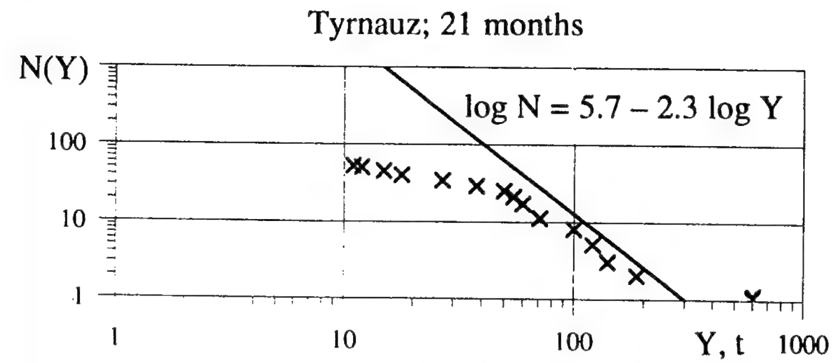
Safronovo; 6 months



Baikal region ; Jul-Oct, 1991; and Jun-Sep, 1992

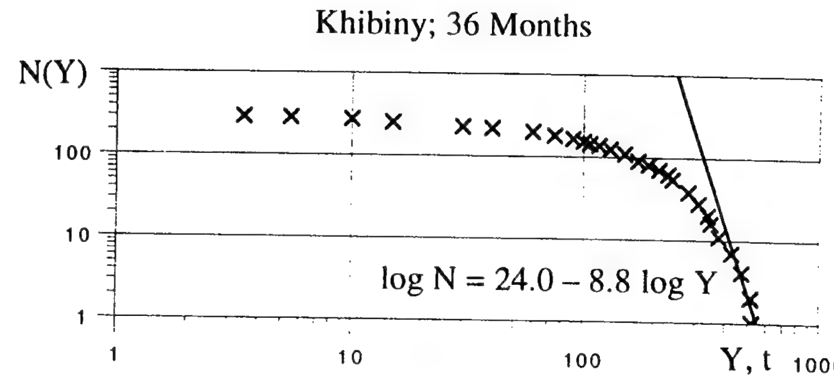
Figure 4

Figures 1 to 4. *Y* distributions for four mines in the Baikal region of Siberia. A few of these blasts exceed 100 tons each. Data for these four mines are all from Leonid Delitsin (personal communication).



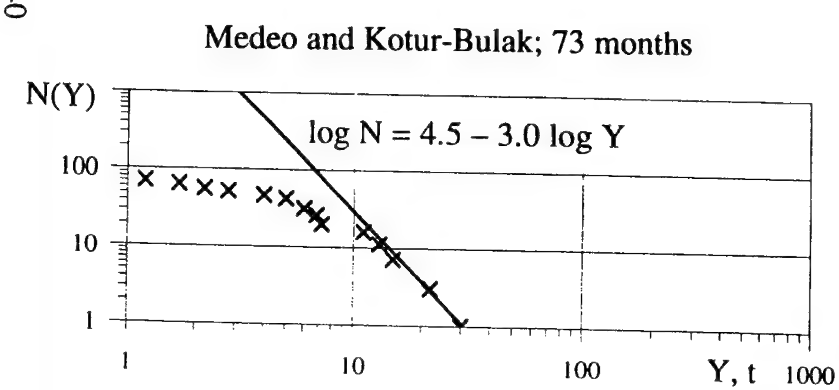
43.3-44.2N, 41.8-43.1E ; Jan-Oct,1980; Feb-Dec,1981

Figure 5. *Y* distribution for a large mine in the South Caucasus (data from Godzikovskaya et al, 1991).



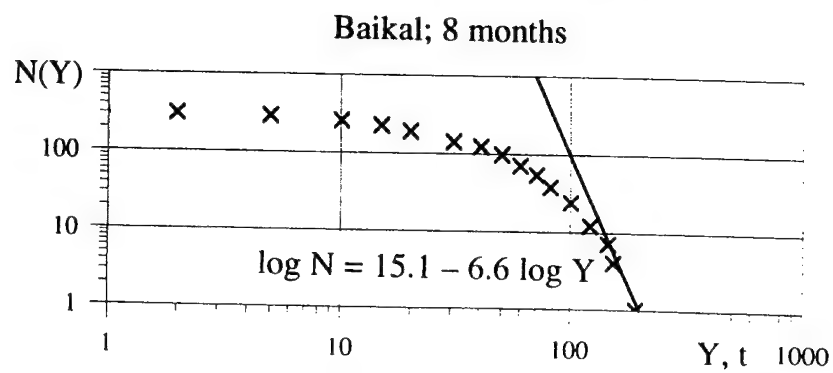
67.67-70.81 N; 33.38-34.15 E ; Jan 1991-Dec 1993

Figure 6. *Y* distribution for a number of mines in the Khibiny massif on the Kola Peninsula (data for Jun 1991-Sep 1992 from Mykkeltveit, 1992; data for Jan 1991-Dec 1993 from Kremenetskaya et al 1995).



43.2N, 77.1E; 43.25N, 77.1E ; Jun 1972-Jun 1976

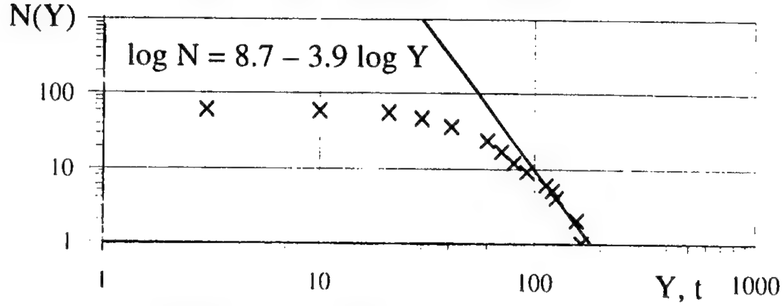
Figure 7. *Y* distribution for two mines in the North Tien Shan region of S.E. Kazakstan (data from Galperin et al, 1978).



48-58N; 100-120E ; Jun-Oct,1991; and Jul-Sep,1992

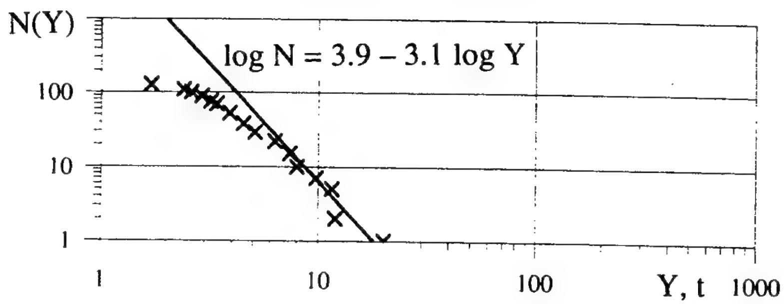
Figure 8. A summary *Y* distribution for the broad Baikal region (data from Leonid Delitsin, personal communication).

Gold mine, Nevada; 5 Months



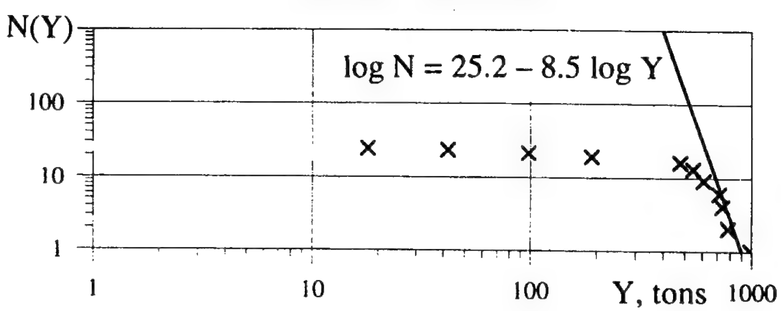
40.96 N; 116.39 E ; Apr 11-Sep 20, 1995

Tekely; 12 months



44.65-44.85 N, 78.85-78.98 E ; Jan 1993 - Dec 1993

Ukraine; 1.8 months



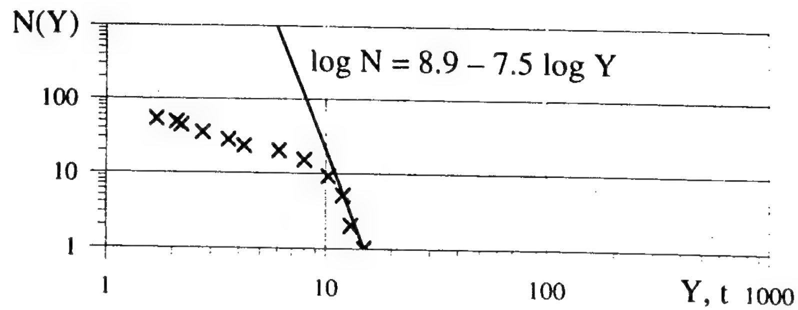
47.4-50.6 N; 28.3-34.9 E ; Jun.16-Aug.12, 1987

Figure 9. *Y* distribution for a typical small western U.S. open pit mining operation (data from Jarpe et al, 1996).

Figure 10. *Y* distribution for small explosions in Israel (data from Gitterman et al, 1993 and 1996).

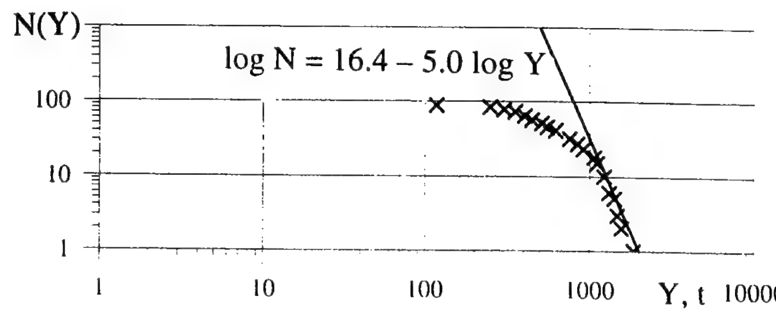
Figure 11. *Y* distribution for four small mines in North Tien Shan (data from N. Mikhailova, personal communication).

Israel; 25 Months



31.1-32.9 N; 35.0-35.8 E ; Jun 1989-Jul 1991

Kursk MA; 36 months

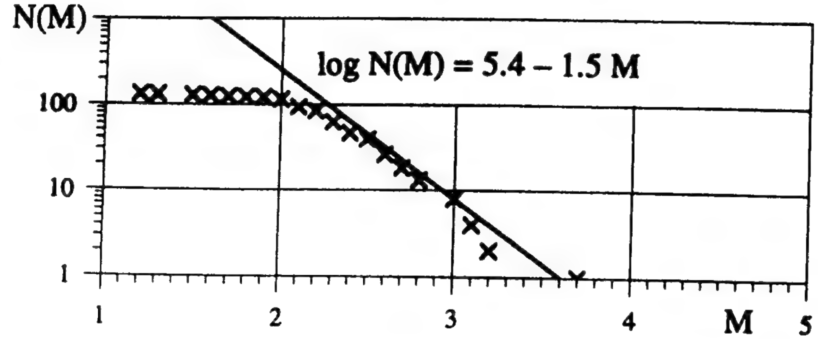


51.3-52.3N, 35.3-37.7E ; 1992-1994

Figure 12. *Y* distribution for a very active mining region for iron ore in the Kursk Magnetic Anomaly region, a few hundred km south of Moscow, indicating large and numerous blasts (data from Leith et al, 1997).

Figure 13. *Y* distribution for an active region with large charge sizes in Ukraine (data from B. Pustovitenko, personal communication).

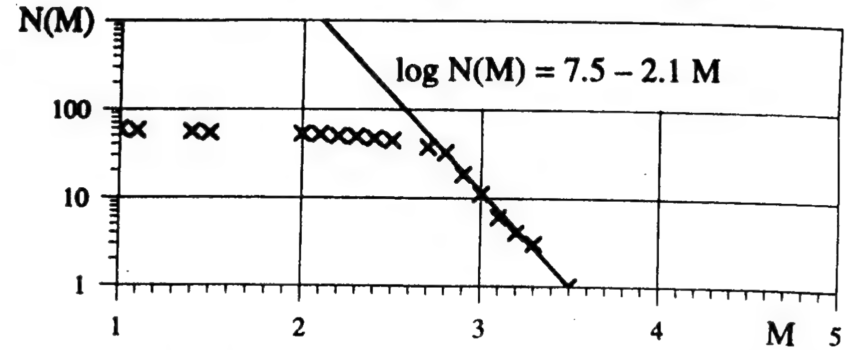
Germany; 18 months



49-52N, 6-13E ; Jan 1994-Jun 1995

Figure 14

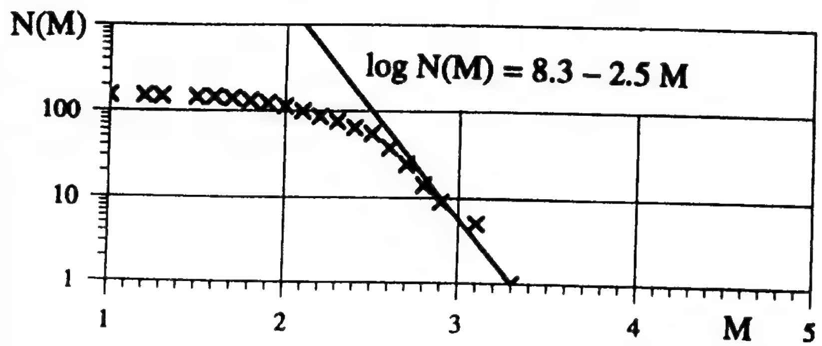
France, Czech+Slovak Republics; 18 mo.



43.2-43.4N, 5.3-5.5E; 49.4-50.5N, 13.2-14.2E ; '94-Jun '95

Figure 15

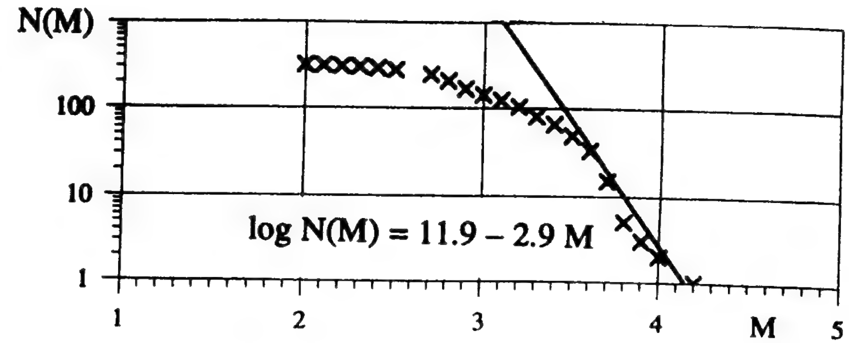
Scandinavia; 18 months



N Norway & Sweden, S Norway ; Jan'94-Jun'95

Figure 16

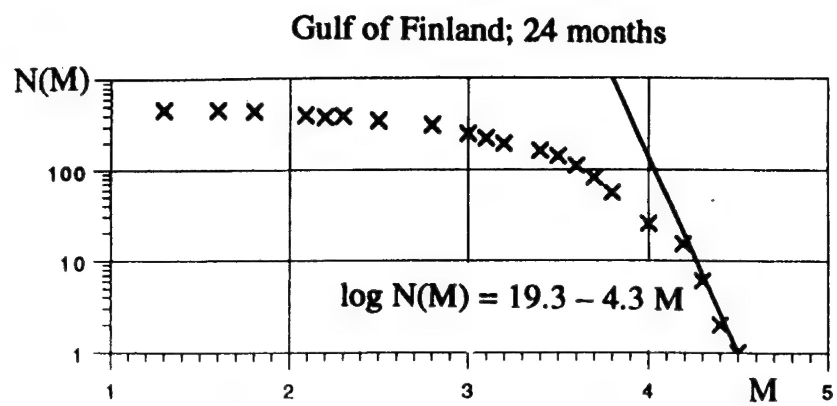
Poland; 18 months



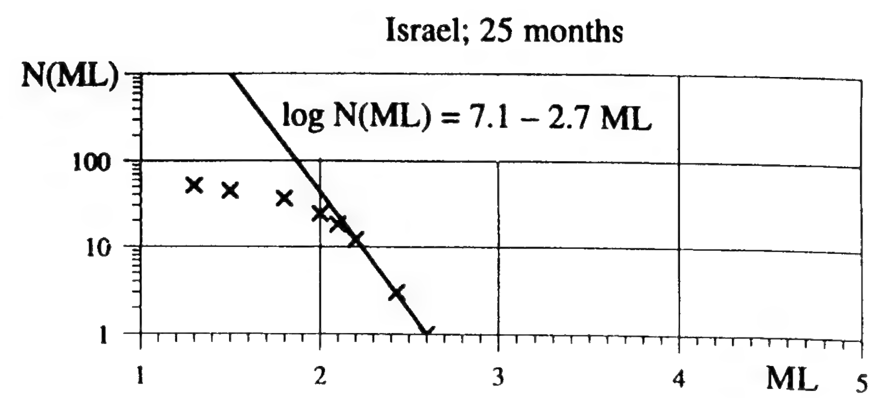
50-53N, 15-19E ; Jan 1994-Jun 1995

Figure 17

Figures 14 to 17. Magnitudes for Germany (Figure 14), parts of Southern France and the Czech and Slovak Republics (Figure 15), Scandinavia (Figure 16), and Poland (Figure 17). Data are from ISC lists of probable explosions. Only the events in Poland show significant activity above magnitude 3.5 (around 4 per month).



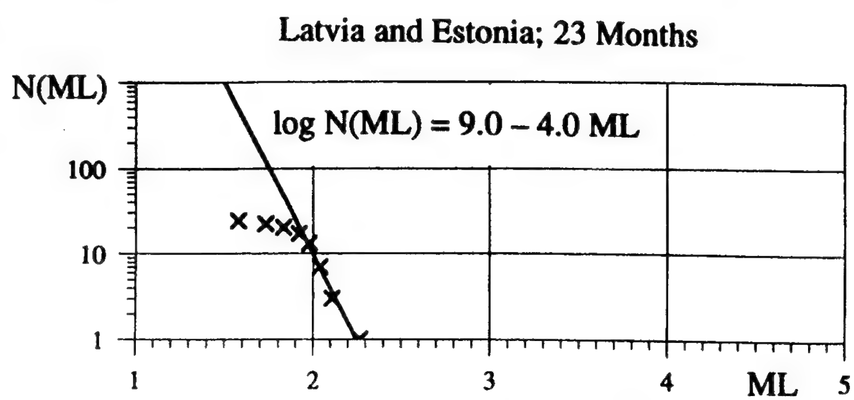
59-61 N, 22-30 E ; Jan 1995-Dec 1996



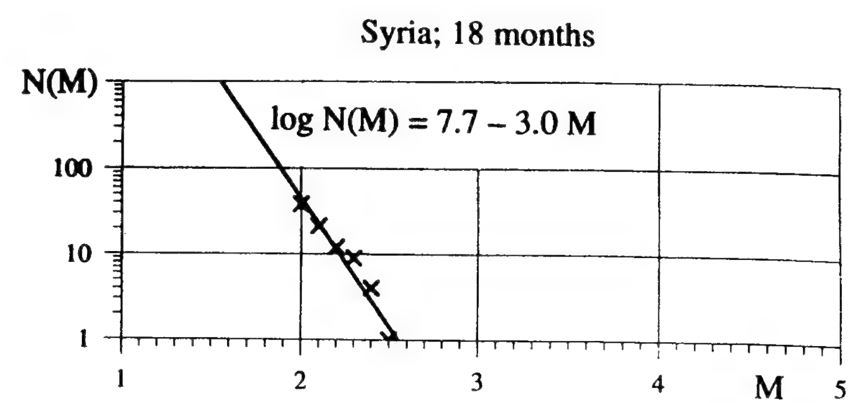
31.1-32.9 N, 35.0-35.8 E ; Jun 1989-Jul 1991

Figure 18. Magnitudes reported by the GSETT-3 International Data Center for the Gulf of Finland during the first two years of operation of this IDC. Although this distribution extends upwards to indicate more than one event per month with $M \geq 4$, it is likely that something is wrong with the magnitude scale.

Figure 19. ML magnitudes for industrial blasting in Israel (data from Gitterman, 1993).



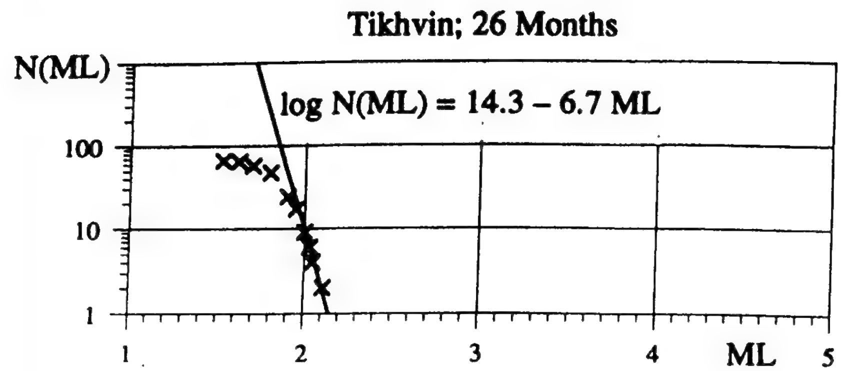
56.15-56.7 N, 22.15-23.8 E ; Dec 1990-Nov 1992



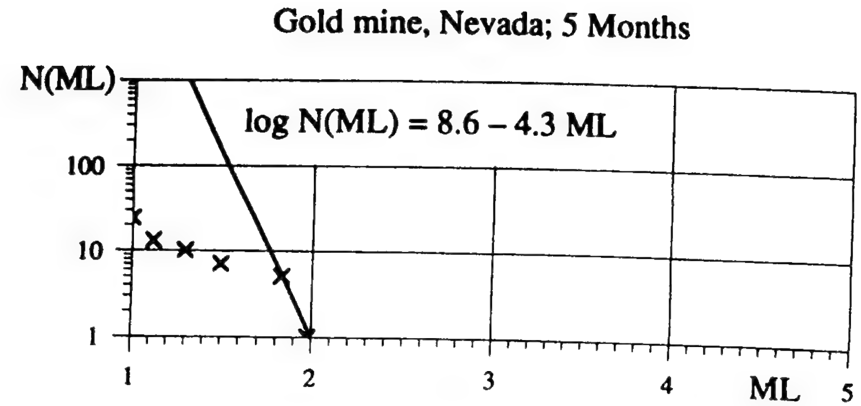
33.2-34N, 35.2-34E ; Jan 1994-Jun 1995

Figure 20. ML magnitudes of mines in Latvia and Estonia (data from Rivière-Barbier, 1993).

Figure 21. Magnitudes for Syria. Data are from ISC lists of probable explosions.



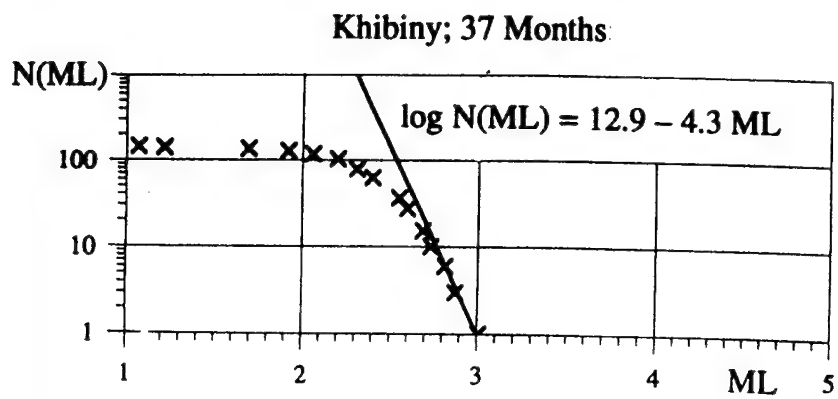
59.2-60.0 N, 33.7-34.7 E ; Nov 1990-Jan 1993



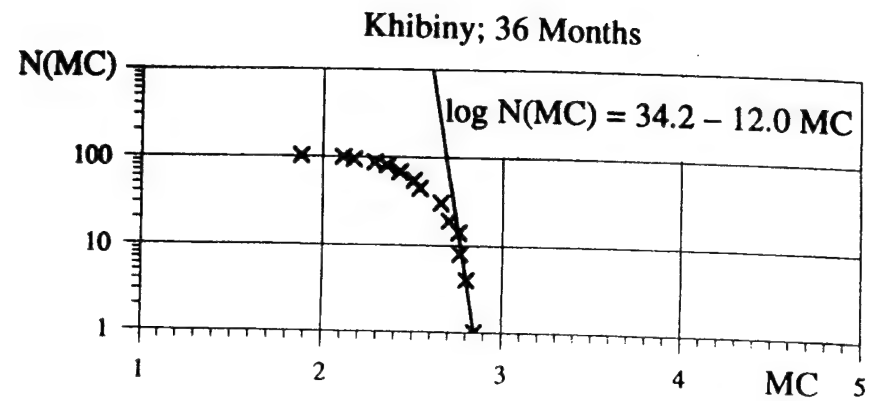
40.96 N, 116.39 E ; Apr 11-Sep 20, 1995

Figure 22. Magnitudes for mines in the Tikhvin region (data from Rivière-Barbier, 1993).

Figure 23. ML magnitudes for a gold mine in Nevada (data from Jarpe et al 1996).



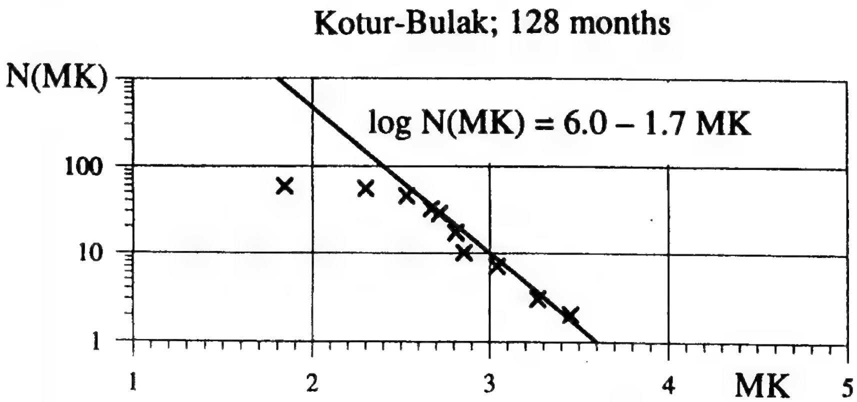
67.67-70.81 N, 33.38-34.15 E ; Dec 1990-Dec 1993



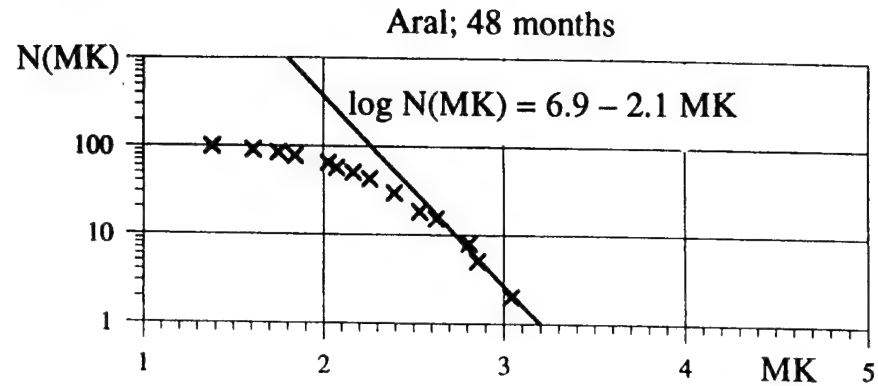
67.67-70.81 N, 33.38-34.15 E ; Jan 1991-Dec 1993

Figure 24. ML magnitudes of mines in the Khibiny massif (data from Kremenetskaya et al, 1995; and Rivière-Barbier, 1993). The slope is quite large at the higher magnitudes.

Figure 25. MC magnitudes of mines in the Khibiny massif (data from Kremenetskaya et al, 1995). A very sharp cut-off is apparent around MC 2.7 to 2.8, perhaps indicating saturation of this magnitude scale.



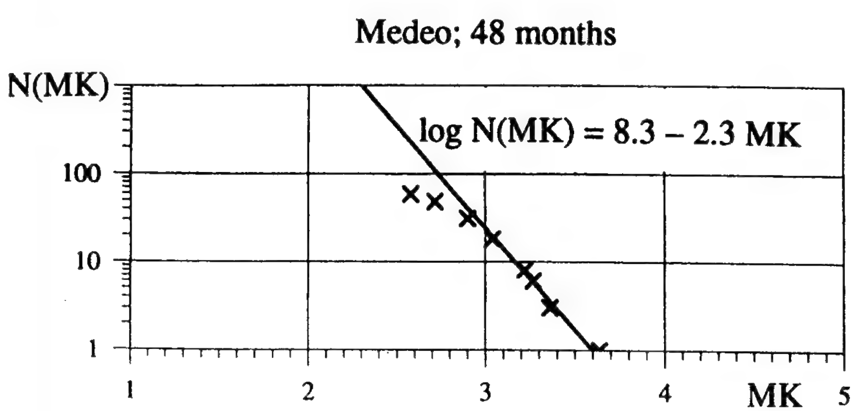
43.25 N, 77.10 E ; Jun'72 - Jun'76, May'88 -Feb'95



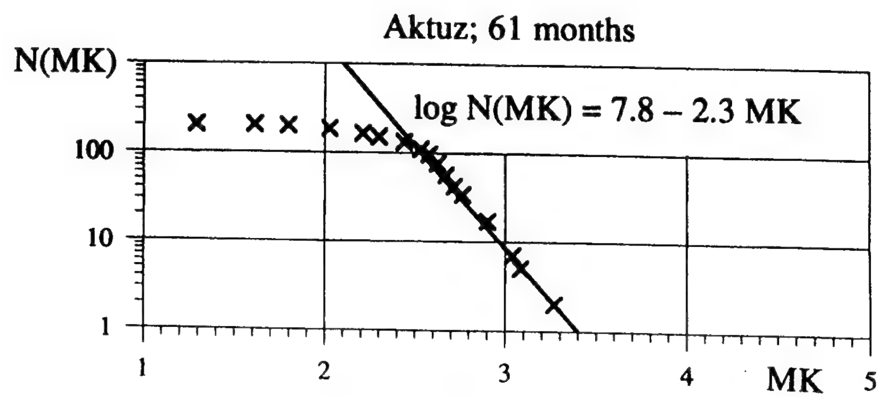
41.81 N, 74.32 E ; Jan 1988-Dec 1991

Figure 26. *MK* magnitudes for the Kotur-Bulak mine in North Tien Shan (data from Galperin et al, 1978, and N. Mikhailova, personal communication).

Figures 27. *MK* magnitudes for the Aral mine in North Tien Shan (data from N. Mikhailova, personal communication).



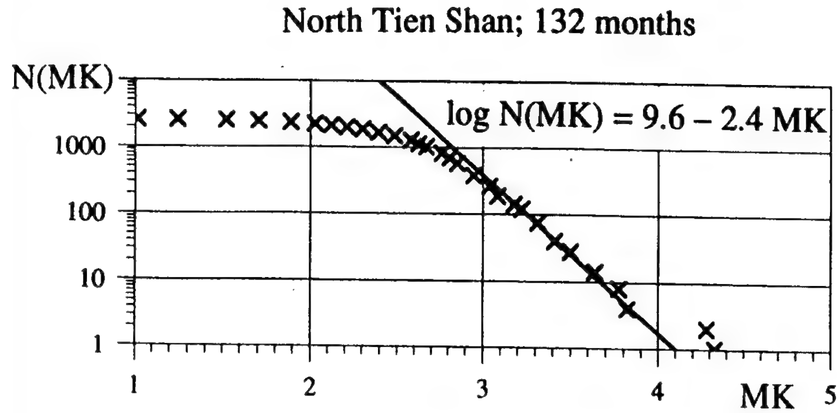
43.17 N, 77.08 E ; Jun 1972-Jun 1976



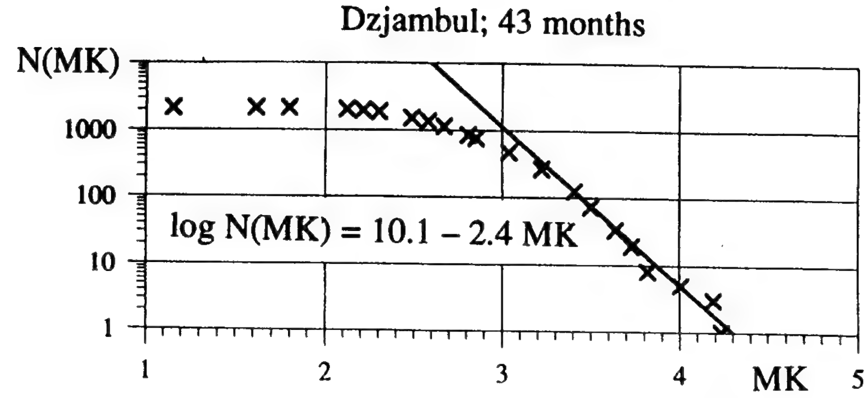
43.88 N, 76.08 E ; May 1988-Jun 1993

Figure 28. *MK* magnitudes for the Medeo mine in North Tien Shan (data from Galperin et al, 1978, and N. Mikhailova, personal communication).

Figure 29. *MK* magnitudes for the Aktuz mine in North Tien Shan (data from N. Mikhailova, personal communication).



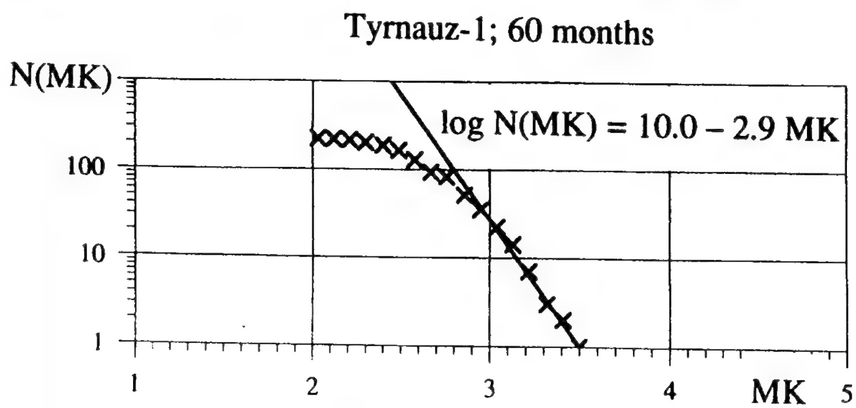
41.8-45.3 N, 74.3-79.2 E ; 1972-1976, 1988-1995



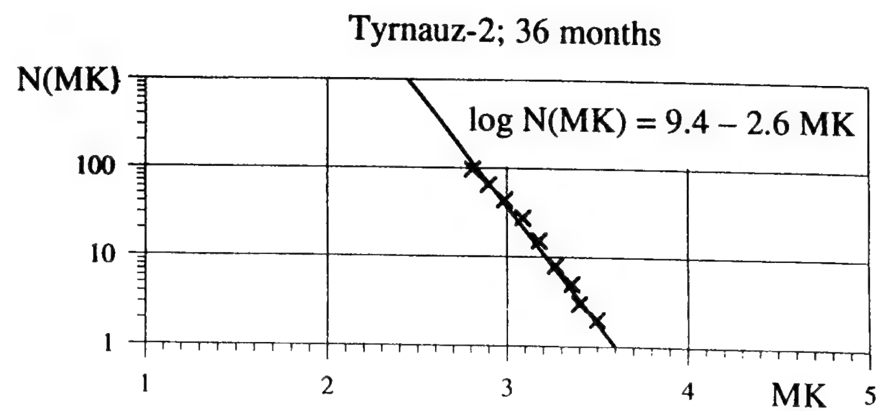
42-44 N, 68-71 E ; Jun 1988-Dec 1991

Figure 30. A composite for the North Tien Shan region, of *MK* magnitudes (data from Galperin et al, 1978, and N. Mikhailova, personal communication). About one blast per year occurs above *MK* 3.5.

Figure 31. *MK* magnitudes for the Dzjambul mine in South Central Kazakstan (data from N. Mikhailova, personal communication), showing about two blasts per month with $MK \geq 3.5$.



43.3-44.2 N, 41.8-43.1 E ; 1977-1981

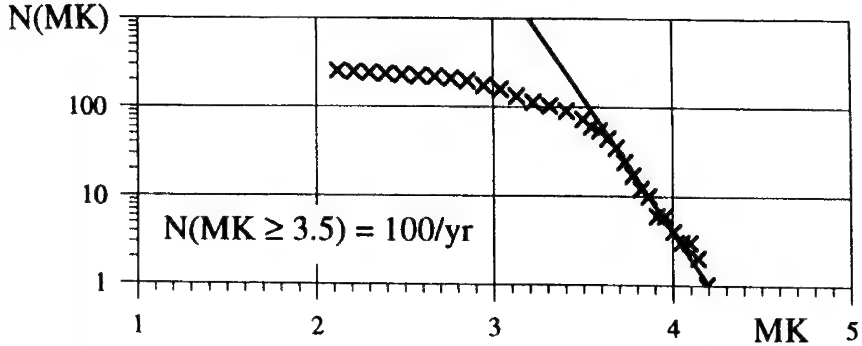


43.3-44.2 N, 41.8-43.1 E ; 1982-1984

Figures 32 and 33. *MK* magnitudes for the Tyrnauz mine in the South Caucasus. These events were wrongly included as earthquakes, in the seismicity catalog of the Caucasus region. Data are for two different times, and show a consistent distribution for these two periods at the higher magnitude range (data from Godzikovskaya et al, 1991). Only five blasts reach *MK* 3.5 over an eight year period. For seismological methods to discriminate between earthquakes and explosions in this region, see Kim et al (1997).

Sayan 1992; 12 months

log N(MK) = 12.6 – 3.0 MK

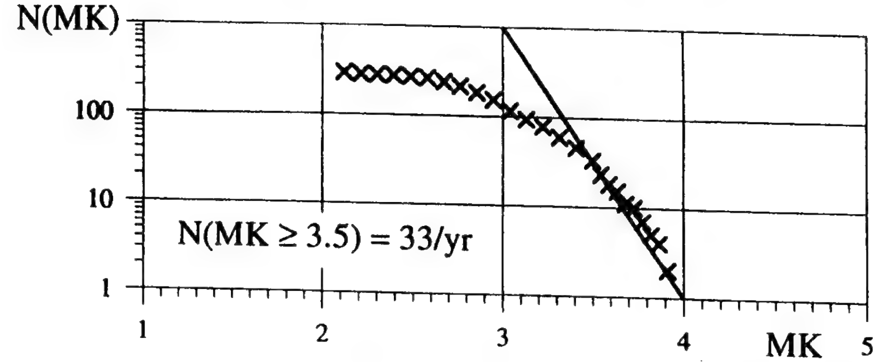


51-54 N; 88-94 E ; Jan-Dec 1992

Figure 34

Sayan 1994; 12 months

log N(MK) = 12.0 – 3.0 MK

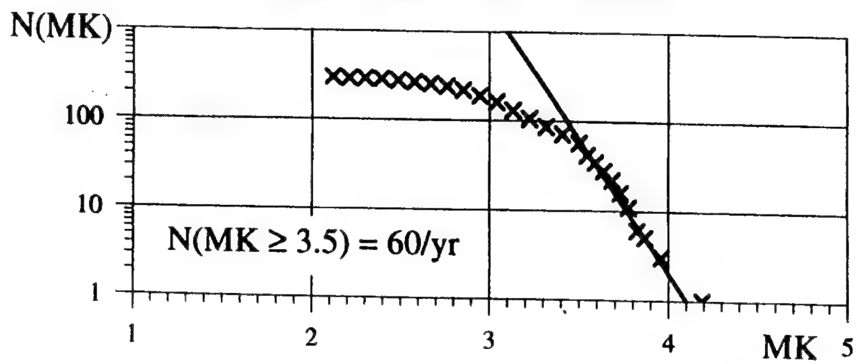


51-54 N; 88-94 E ; Jan-Dec 1994

Figure 35

Sayan 1993; 12 months

log N(MK) = 12.3 – 3.0 MK

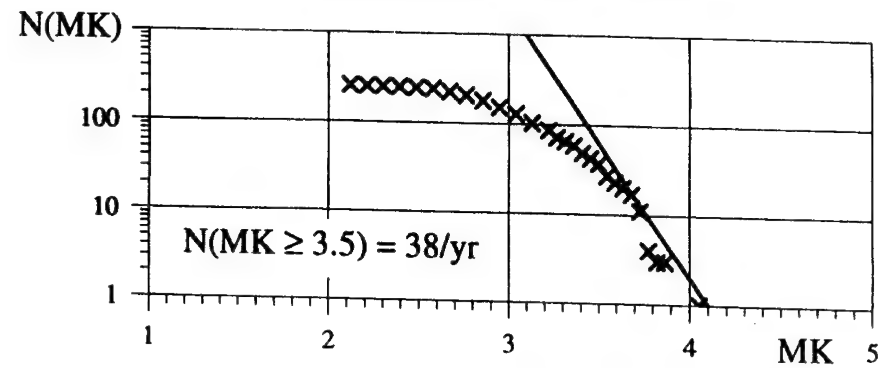


51-54 N; 88-94 E ; Jan-Dec 1993

Figure 36

Sayan 1995; 12 months

log N(MK) = 12.3 – 3.0 MK

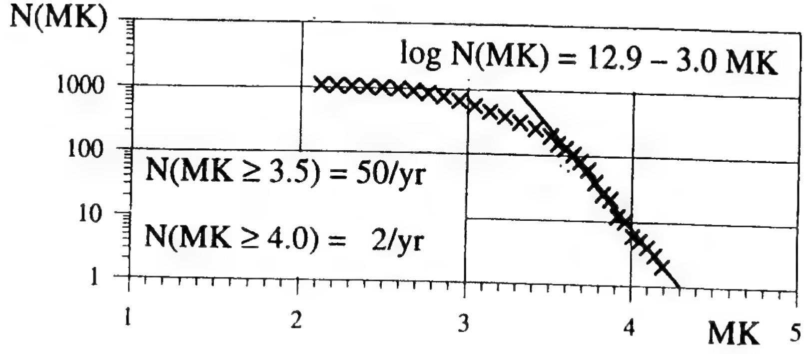


51-54 N; 88-94 E ; Jan-Dec 1995

Figure 37

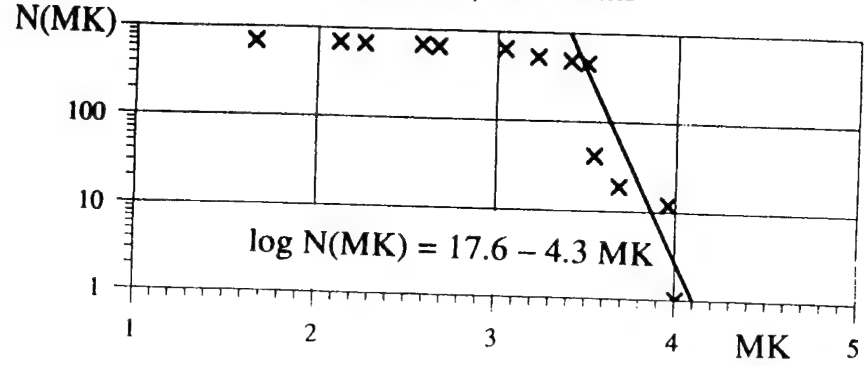
Figures 34 to 37. *MK* magnitudes for the Sayan region of Western Siberia, a few hundred km to the east of the Kuzbass region (data from A. Filina and A. Godzikovskaya, personal communication). Most of these blasts originate in one of the two large mines near Abakan. These figures show the distribution for four different years. There is little variation from year to year.

Sayan-total; 53 months



51-54 N; 88-94 E ; Aug 1991-Dec 1995

Kuzbass; 56 months

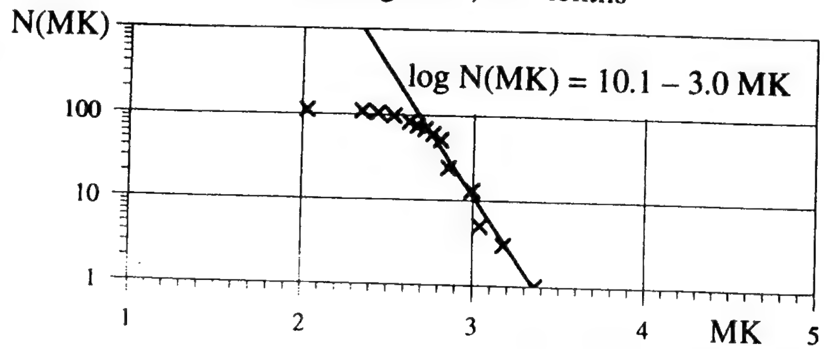


50.5-53.0 N, 83.5-88.0 E ; Jan 1989-Aug 1993

Figure 38. A summary of *MK* magnitudes for the Sayan region for a 53 month period. There are several tens of blasts with $MK \geq 3.5$ each year, and about two with $MK \geq 4$ each year. Such blasting activity is likely to lead to numerous detections by CTBT monitoring networks.

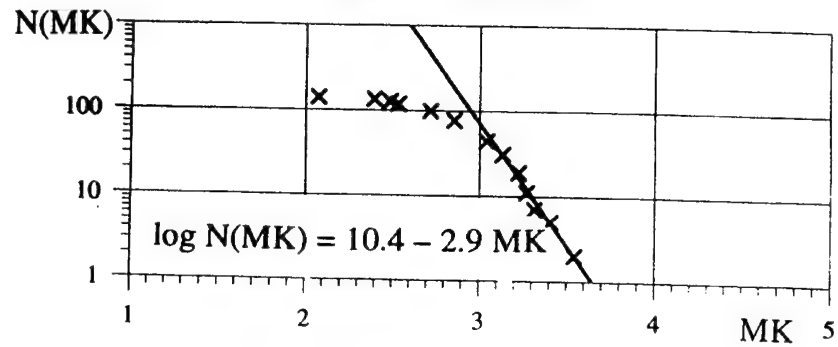
Figure 39. *MK* magnitudes for the Kuzbass mining region in the Altai area of Western Siberia (data from A. Filina and A. Godzikovskaya, personal communication). The reason for the uneven distribution at higher magnitudes, is probably that *K* values were reported only to the nearest integer during part of the 56 month time period. There are about 100 blasts per year with $MK \geq 3.5$, probably large enough for detection by CTBT monitoring networks.

Georgievka; 48 months



43.03 N, 74.43 E ; May 1988-May 1992

Primorie; 23 months

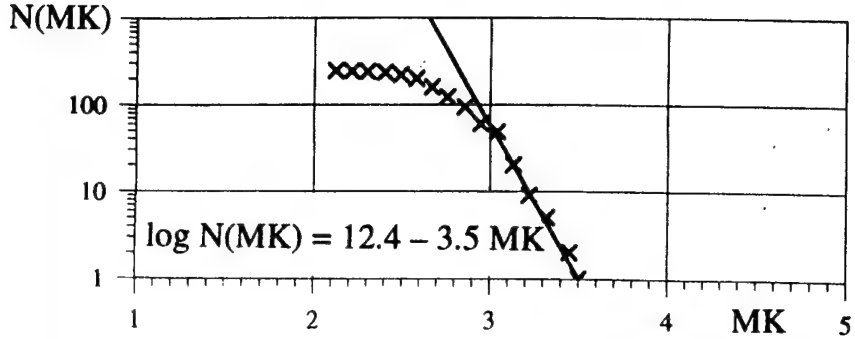


43-56 N, 123-139 E ; Feb 1990-Dec 1991

Figure 40. *MK* magnitudes for the Georgievka mine in North Tien Shan (data from N. Mikhailova, personal communication).

Figure 41. *MK* magnitudes for Primorie (the Russian Far East), showing very few events per year with $MK \geq 3.5$ (data from Godzikovskaya, 1995).

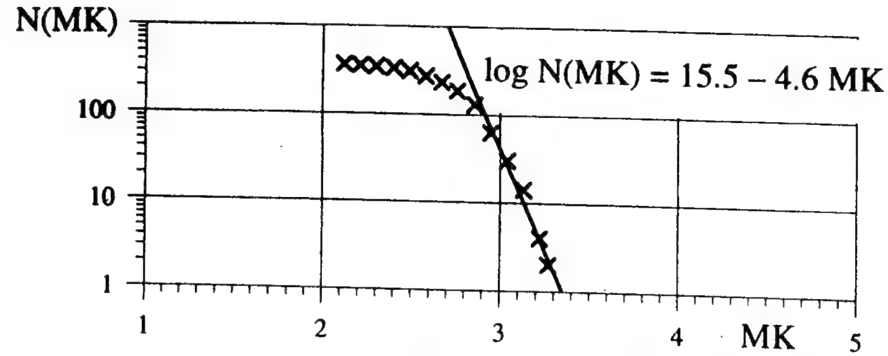
Mandeuli-1; 36 months



41.22 N, 44.28 E ; Jan 1975-Dec 1977

Figure 42

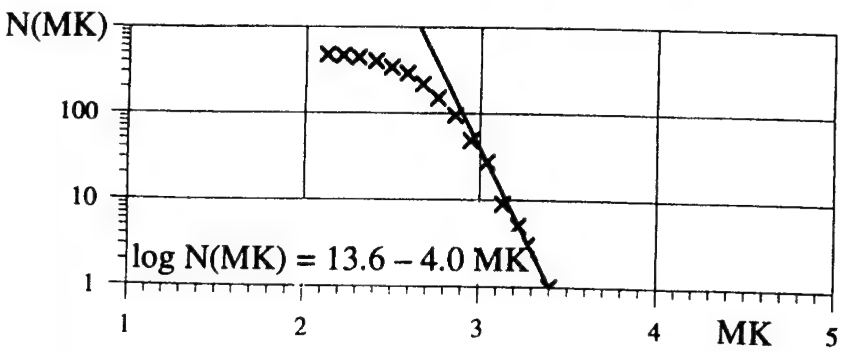
Mandeuli-2; 30 months



41.22 N, 44.28 E ; Jul 1980-Dec1982

Figure 43

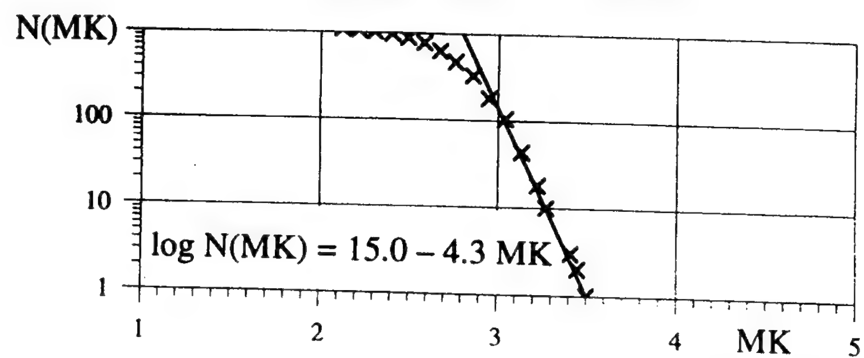
Mandeuli-3; 66 months



41.22 N, 44.28 E ; Jan 1983-Jun 1988

Figure 44

Mandeuli-total; 132 months



41.22 N, 44.28 E ; 1975-1988

Figure 45

Figures 42 to 45. *MK* magnitudes for the Mandeuli mines in Georgia, shown for three different time periods, and in total over more than ten years (data from Godzikovskaya et al, 1991). We see a fairly consistent distribution of the magnitudes for different time periods, though there is a slight decrease of the larger magnitudes with time, and a slight increase in the smaller magnitudes. Only a few blasts reach more than *MK* 3.3.

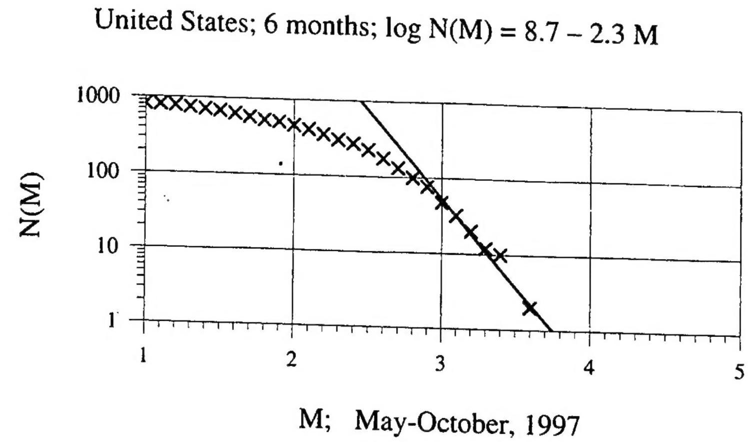


Figure 46. Magnitudes for mining seismicity in the United States for six months of 1997 (data from a new USGS bulletin described by http://earthquake.usgs.gov/neis/mineblast/).

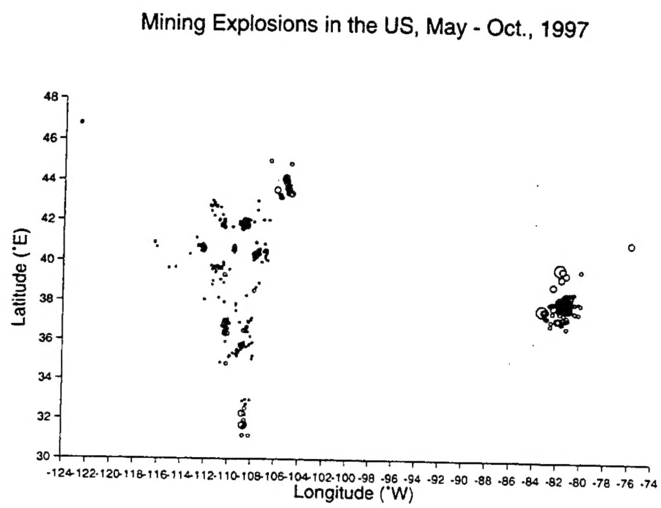


Figure 47. Spatial distribution of U.S. mining seismicity, with symbol size proportional to magnitude (data from a USGS bulletin on mining seismicity).

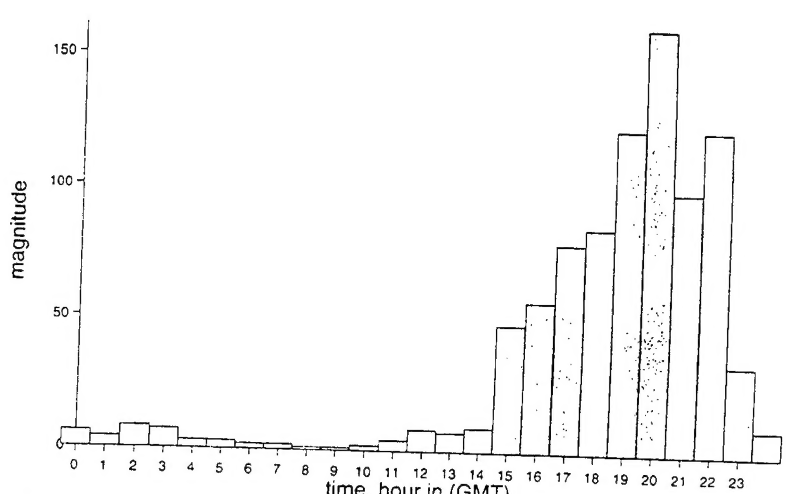


Figure 48. Distribution of U.S. mining seismicity, as a function of GMT time of day (data from a USGS bulletin on mining seismicity).

of the Altai-Sayan indeed generate air blasts that are detectable over significant distances via infrasound. If both seismic and infrasound sensors routinely pick up strong signals from large mine blasts, then an absence of radionuclides can build confidence in CTBT compliance.

ACKNOWLEDGEMENTS

We appreciate the assistance of Albina G. Filina from the Institute of Geophysics in Novosibirsk, Natalya N. Mikhailova from the Talgar Complex Seismological Expedition, and Anna Godzikovskaya, Leonid Delitsin, and B. Pustovitenko. Thanks also to Jim Dewey for information, and Won-Young Kim for analysis, concerning U.S. mining seismicity. This research was sponsored by the Department of Energy and monitored by the Air Force Phillips Laboratory under contract F19628–95–C–0100.

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For part 3 of this Final Report, we note that the following paper by the Principal Investigators (Kim and Richards) was published in the June 1997 issue of the Bulletin of the Seismological Society of America; and that the substance of the paper was presented by Paul G. Richards November 1997 at an Event Screening Workshop held in Beijing under the auspices of the Provisional Technical Secretariat of the CTBT Organization:

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Discrimination of Earthquakes and Explosions in Southern Russia Using Regional High-Frequency Three-Component Data from the IRIS/JSP Caucasus Network

by W.-Y. Kim, V. Aharonian, A. L. Lerner-Lam, and P. G. Richards

Abstract High-frequency regional records from small earthquakes (magnitude <4.5) and comparable magnitude chemical explosions are analyzed to find a reliable seismic discriminant in southern Russia near Kislovodsk. The digital, three-component seismograms recorded during 1992 by the Caucasus Network operated by Lamont-Doherty Earth Observatory since 1991 in the distance ranges 15 to 233 km are used. Mean vertical-component *Pg/Lg* spectral amplitude ratios in the band 8 to 18 Hz are about 1.3 and 3.2 for earthquakes and explosions, respectively, in this region. We find that the vertical-component *Pg/Lg* spectral ratio in the frequency band 8 to 18 Hz serves quite well for classifying these events. A linear discriminant function analysis indicates that the *Pg/Lg* spectral ratio method provides discrimination power with a total misclassification probability of about 7%. The *Pg/Lg* spectral ratios of rotated, three-component regional records improve the discrimination power of the spectral ratio method over the vertical-component *Pg/Lg* ratios. Preliminary analysis indicates that distance-corrected vertical-component *Pg/Lg* ratios improve the discrimination power by about 4% over uncorrected ratios. But we find that an even better discriminant is the *Pg/Lg* spectral ratio of the three-component regional records corrected for the free-surface effect. In the frequency band 8 to 18 Hz, the free-surface-corrected three-component *Pg/Lg* spectral ratio provides discrimination power with a total misclassification probability of only 2.6%. Free-surface-corrected and network-averaged *Pg/Lg* spectral ratios provide transportability of the spectral ratio method to various regions worldwide.